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SYSTEMS STUDY FOR CONTROL OF EMISSIONS PRIMARY NONFERROUS SMELTING INDUSTRY. VOLUME III. APPENDICES C THROUGH G

Arthur G. McKee and Company
San Francisco, California

June 1969

PB 184886

SYSTEMS STUDY FOR CONTROL OF EMISSIONS PRIMARY NONFERROUS SMELTING INDUSTRY

VOLUME III of III: APPENDICES C through G

FINAL REPORT UNDER CONTRACT PH 86-65-85

FOR
DIVISION OF PROCESS CONTROL ENGINEERING
NATIONAL AIR POLLUTION CONTROL ADMINISTRATION
PUBLIC HEALTH SERVICE
U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE

JUNE 1969

ARTHUR G. McKEE & COMPANY
WESTERN KNAPP ENGINEERING DIVISION
SAN FRANCISCO, CALIFORNIA

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McKEE REPORT NO. 993

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APPENDIX C

SMELTER MODELS MATCHED WITH CONTROL PROCESSES

Models, Control Schemes, and Matching:

Table No.

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SUMMARY OF SMELTER

COPPER

		Model A	
		Reverb	Converter
Number of equipment units		1	2
Copper production capacity	tons per day		
	tons per year		
Sulfur equivalent of sulfur oxides generated	tons per day	84.6	158.9
	tons per year	27,900	52,400
Offgas after air dilution			
Temperature	°F	550	640
Sulfur oxides	volume %	1.89	3.8

The figures given above apply to the small plant. For the medium plant multiply tons and equipment units by two, for large plant multiply by three.

ZINC

		Model A		
		Roasting	Sintering	Other
Zinc production capacity	tons per day			
	tons per year			
Sulfur equivalent of sulfur oxides generated	tons per day	89.6	0.9	1.4
	tons per year	29,600	300	400
Offgas after air dilution				
Temperature	°F	600	500	
Sulfur oxides	volume %	7.2	.05	
Oxygen	volume %	10.9	18.	

The figures given here apply to the small size plants. For the medium plants multiply tons by two, for large plants multiply by three.

(concluded on next sheet)

A.

Appendix C
Table C - 1
Sheet 1 of 2

SUMMARY OF SMELTER MODELS

Model A			Model B			
Reverb	Converter	Total	Roaster	Reverb	Converter	Total
1	2		1	1	2	
		230				230
		75,900				75,900
84.6	158.9	243.5	183.8	24.6	141.6	350
27,900	52,400	80,300	60,700	8,100	46,700	115,500
550	640		550	550	640	
1.89	3.8		8.0	.9	3.8	

The copper model year has 330 days.
See Plates C-1 and C-2 in this appendix for details of copper smelter models A and B, small size.

Model A				Model B		Model C	Model D
Roasting	Sintering	Other	Total	Roasting	Sintering	Roasting	Sintering
			171.4 (all models)				
			56,600 (all models)				
89.6	0.9	1.4	91.9	77.1	15.4	90.9	92.6
29,600	300	400	30,300	25,400	5,100	30,000	30,600
600	500			600	300	400	300
7.2	.05			.9	.5	.8	2.0
10.9	18.			18.	18.	16.	16.

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The zinc model year has 330 days.
See Plate C-4 for details of zinc smelter model A. The plant shown on Plate C-4 is 2.5 times the size of a small plant; i.e., it is between a medium and a large plant in size.

B.

LEAD		Model A		
		Sintering	Blast Furnace	Other
Lead production capacity	tons per day			
	tons per year			
Sulfur equivalent of sulfur dioxide generated	tons per day	34.3	0.3	0.4
	tons per year	11,300.	100.	100.
Offgas after air dilution				
Temperature	^oF	400		
Sulfur dioxide	volume %	5.0	.06	
Sulfur trioxide	volume %	.29		
Oxygen	volume %	12.	4.	

The figures given here apply to the small plant. For the medium plant multiply tons by two, for the large plant multiply by four.

The l
See t

A.

Appendix C
Table C - 1
Sheet 2 of 2

Model A			
Sintering	Blast Furnace	Other	Total
			142.9
			47,200.
34.3	0.3	0.4	35.0
11,300.	100.	100.	11,500.
400			
5.0	.06		
.29			
12.	4.		

The lead model year has 330 days.
See text for discussion of this model.

B.

SULFUR OXIDE CONTROL SCHEMES MATCHED WITH COPPER SMELTER MODELS

Model A: (Reverberatory furnace and converters)

Scheme

1. Combined offgases from reverb and converters all go to scrubber for absorption by lime slurry.
2. As for Scheme 1, except scrubber uses limestone slurry.
3. Reverb offgas to Cominco absorption unit, Cominco sulfur dioxide product gas mixed with converter offgas goes to sulfuric acid plant. Cominco and acid plant tail gases to stack.
4. As for Scheme 3, except combined stream of strong gases goes to Asarco reduction process.
5. In the small plant, all offgases go to limestone slurry scrubbing. In the medium plant, 90 percent of the converter offgas and in the large plant 100 percent goes to the acid plant, any remainder goes with reverb offgas to limestone slurry scrubbing. Acid plant and scrubber tail gases to stack.
6. As for Scheme 5, except Asarco reduction process replaces acid plant.

Model B: (Roaster, reverb, converters)

Scheme

7. Combined offgases from all smelter units go to lime slurry scrubbing.
8. As for Scheme 7, except limestone slurry scrubbing.
9. Reverb offgas to Cominco absorption unit, Cominco product gas combined with roaster and converter offgases and all go to sulfuric acid plant. Cominco and acid plant tailgases to stack.

10. As for Scheme 9, except combined gases go to Asarco reduction process.
11. Roaster and converter offgases combined go to sulfuric acid plant, reverb offgas to limestone slurry scrubbing.
12. As for Scheme 11, except roaster and converter offgases go to Asacro reduction process.

SULFUR OXIDE CONTROL SCHEMES MATCHED WITH ZINC SMELTER MODELS

Model A: (Roaster, dryer, sinter machine, coker and retort. Roaster offgas is strong in sulfur oxides, other offgases very weak.)

Scheme

1. Roaster offgas goes to sulfuric acid plant, all other gas to stack.
2. As for Scheme 1, except roaster gas to Asarco reduction process.
3. Roaster offgas to lime slurry scrubbing. Scrubber tail gas and other smelter offgases to stack.
4. As for Scheme 3, except limestone slurry scrubbing.

Model B: (Roaster, sinter machine, coker and retort. All offgases weak in sulfur oxides.)

Scheme

5. All roaster offgas and portion of sintering machine offgas go to Cominco absorption unit. Cominco product gas and remainder of sintering offgas go to sulfuric acid plant. Other offgases and Cominco and acid plant tail gases to stack.
6. As for Scheme 5, except Asarco reduction process replaces acid plant.
7. Roaster and sintering machine offgases to lime slurry scrubbing. Scrubber tail gas and other smelter offgases to stack.
8. As for Scheme 7, except limestone slurry scrubbing.

Model C: (Roaster only, offgas weak)

Scheme

9. Roaster offgas to Cominco absorption, Cominco product gas to sulfuric acid plant, all tail gases to stack.
10. As for Scheme 9, except Asarco reduction process replaces acid plant.
11. Roaster offgas to lime slurry scrubbing.
12. Roaster offgas to limestone slurry scrubbing.

Model D: (Sintering machine only, offgas with two percent sulfur oxides.)

Scheme

13. As for Scheme 9.
14. As for Scheme 10.
15. As for Scheme 11.
16. As for Scheme 12.
17. Sintering machine offgas goes directly to sulfuric acid plant.

SULFUR OXIDE CONTROL SCHEMES MATCHED WITH LEAD SMELTER MODEL

Model A: (Updraft sintering, blast furnace.)

Scheme

1. Sintering machine offgases go directly to a contact sulfuric acid plant, other smelter offgases and acid plant tail gas go to a stack.
2. As for Scheme 1, except sintering machine offgases go to Asarco reduction process.
3. As for Scheme 1, except sintering machine offgases go to lime slurry scrubbing.
4. As for Scheme 3, except limestone slurry scrubbing.

RESULTS OF MATCHING CONTROL SC

	Units	small	medium	large
Scheme number		1		
Plant size		small	medium	large
Copper production	1000 tons per yr	75.9	152.	228.
Sulfur equivalent in offgases	1000 tons per yr	80.3	161.	241.
Control process used:		lime slurry scrubbing		
Capital cost	$ millions	5.75	10.90	16.2
Operating cost, gross	$ millions per yr	2.89	5.63	8.27
	¢ per lb copper	1.9	1.9	1.8
Byproduct No. 1			waste	
Production	1000 tons per yr	351.	702.	1,053.
Byproduct No. 2				
Production	1000 tons per yr			
Sulfur equivalent lost to stack	1000 tons per yr	8.	16.1	24.1
Overall sulfur recovery	percent	90.	90.	90.

(1) Gross cost from graphs of Section VIII c, with credit to acid plant at $7 per ton for acid used by Cominco unit.

(2) This is net acid production after allowance for acid used by the Cominco unit.

(3) Sulfuric acid is 66° Baume strength. Equivalent tonnage of 100% acid is given.

(Concluded on next sheet)

A.

Appendix C
Table C - 5
Sheet 1 of 2

ING CONTROL SCHEMES WITH COPPER MODEL A

	2			3			4		
large	small	medium	large	small	medium	large	small	medium	large
228.	75.9	152.	228.	75.9	152.	228.	75.9	152.	228.
241.	80.3	161.	241.	80.3	161.	241.	80.3	161.	241.
rubbing	limestone slurry scrubbing			Cominco absorption; sulfuric acid			Cominco absorption; Asarco reduction		
16.2	2.74	4.70	6.46	18.8	36.0	52.0	33.0	60.0	85.0
8.27	2.23	4.16	6.05	4.95(1)	9.6(1)	14.2(1)	9.4	17.8	26.1
1.8	1.5	1.4	1.3	3.3	3.2	3.1	6.2	5.9	5.7
	waste			ammonium sulfate			ammonium sulfate		
1,053.	448.	896.	1,344.	63.	126.	189.	63.	126.	189.
				sulfuric acid (2,3)			sulfur		
				180.	361.	541.	75.	150.	225.
24.1	16.1	32.2	48.2	5.4	10.7	16.1	5.4	10.7	16.1
90.	80.	80.	80.	93.3	93.3	93.3	93.3	93.3	93.3

it to acid

d used by

nnage of

Note:

These costs apply only to the specific conditions of copper smelter model A as described in Table C - 1 and Plate C - 1.

All tons are short tons of 2000 pounds.

B.

	Units
Scheme number	
Plant size	
Copper production	1000 tons per yr
Sulfur equivalent in offgases	1000 tons per yr
a) Control process for converter offgas:	
Portion of converter offgas treated	percent
Capital cost	$ millions
Operating cost, gross	$ millions per yr ¢ per lb copper
Byproduct	
Production	1000 tons per yr
Cost to produce	$ per ton
Sulfur recovery from total offgas	percent
b) Control for remaining offgases:	
Capital cost	$ millions
Operating cost, gross	$ millions per yr ¢ per lb copper
Byproduct	
Production	1000 tons per yr
Sulfur recovery from total offgas	percent
c) Combination of a) and b)	
Capital cost	$ millions
Operating cost, gross	$ millions per yr ¢ per lb copper
Sulfur equivalent lost to stack	1000 tons per yr
Overall sulfur recovery	percent

A.

Appendix C
Table C-5
Sheet 2 of 2

	Units	5			6		
		small	medium	large	small	medium	large
	1000 tons per yr	75.9	152.	228.	75.9	152.	228.
	1000 tons per yr	80.3	161.	241.	80.3	161.	241.
fgas:			sulfuric acid			Asarco reduction process	
reated	percent	none	90	100	none	90	100
	$ millions		8.6	16.0		28.0	45.0
	$ millions per yr		2.2	4.0		6.8	12.0
	¢ per lb copper		.7	.9		2.1	2.6
			sulfuric acid			sulfur	
	1000 tons per yr		244.(3)	457.(3)		80.	159.
	$ per ton		9.00	8.70		85.00	75.70
fgas	percent		50	62		50.	62.
		limestone slurry scrubbing			limestone slurry scrubbing		
	$ millions	2.74	3.0	3.1	2.74	3.0	3.1
	$ millions per yr	2.23	2.19	2.31	2.23	2.19	2.31
	¢ per lb copper	1.5	.7	.5	1.5	.7	.5
			waste			waste	
	1000 tons per yr	448.	428.	467.	448.	428.	467.
fgas	percent	80	38	28	80.	38.	28.
	$ millions	2.74	11.6	19.1	2.74	31.0	48.1
	$ millions per yr	2.23	4.39	6.31	2.23	8.99	14.31
	¢ per lb copper	1.5	1.4	1.4	1.5	2.8	3.1
ck	1000 tons per yr	16.1	20.	25.	16.1	20.	25.
	percent	80.	88.	90.	80.	88.	90.

B.

RESULTS OF MATCHING CONTROL SCHEME

	Units	7			
Scheme number					
Plant size		small	medium	large	sm
Copper production	1000 tons per yr	75.9	152.	228.	7
Sulfur equivalent in offgases	1000 tons per yr	115.5	231.	346.	11
Control process used:		lime slurry scrubbing			l
Capital cost	$ millions	8.00	15.25	23.45	
Operating cost, gross	$ millions per yr	3.98	7.76	11.61	
	¢ per lb copper	1.7	1.7	1.7	
Byproduct No. 1		waste			
Production	1000 tons per yr	504.	1,008.	1,512.	64
Byproduct No. 2					
Production	1000 tons per yr				
Sulfur equivalent lost to stack	1000 tons per yr	11.6	23.1	34.7	2
Overall sulfur recovery	percent	90.	90.	90.	8

(1) Gross cost from graphs of Section VIII c, with credit to acid plant at $7 per ton for acid used by Cominco unit.

(2) This is net acid production after allowance for acid used by the Cominco unit.

(3) Sulfuric acid is 66° Baume strength. Equivalent tonnage of 100% acid is given.

(Concluded on next sheet)

A.

Appendix C
Table C - 6
Sheet 1 of 2

NG CONTROL SCHEMES WITH COPPER MODEL B

	8			9			10		
large	small	medium	large	small	medium	large	small	medium	large
228.	79.5	152.	228.	75.9	152.	228.	75.9	152.	228.
346.	115.5	231.	346.	115.5	231.	346.	115.5	231.	346.
ubbing	limestone slurry scrubbing			Cominco absorption; sulfuric acid			Cominco absorption; Asarco reduction		
23.45	3.35	5.65	7.75	14.4	23.8	35.0	34.7	56.8	80.0
11.61	3.00	5.63	8.21	3.84(1)	6.28(1)	8.47(1)	9.0	15.8	23.1
1.7	1.3	1.2	1.2	2.5	2.1	1.9	5.9	5.2	5.1
	waste			ammonium sulfate			ammonium sulfate		
1,512.	644.	1,288.	1,932.	18.	37.	55.	18.	37.	55.
				sulfuric acid (2,3)			sulfur		
				320.	640.	961.	109.	219.	328.
34.7	23.1	46.2	69.3	6.2	12.4	18.5	6.2	12.4	18.5
90.	80.	80.	80.	94.7	94.7	94.7	94.7	94.7	94.7

t to acid

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Note:

These costs apply only to the specific conditions of copper smelter model B as described in Table C - 1 and Plate C - 2.

All tons are short tons of 2000 pounds.

B.

	Units
Scheme number	
Plant size	
Copper production	1000 tons per yr
Sulfur equivalent in offgases	1000 tons per yr
a) Control process for all roaster & converter offgases:	
Capital cost	$ millions
Operating cost, gross	$ millions per yr
	¢ per lb copper
Byproduct	
Production	1000 tons per yr
Cost to produce	$ per ton
Sulfur recovery from total offgas	percent
b) Control for remaining offgas	
Capital cost	$ millions
Operating cost, gross	$ millions per yr
	¢ per lb copper
Byproduct	
Production	1000 tons per yr
Sulfur recovery from total offgas	percent
c) Combination of a) and b)	
Capital cost	$ millions
Operating cost, gross	$ millions per yr
	¢ per lb copper
Sulfur equivalent lost to stack	1000 tons per yr
Overall sulfur recovery	percent

A.

Appendix C
Table C - 6
Sheet 2 of 2

	Units	11			12		
		small	medium	large	small	medium	large
	1000 tons per yr	75.9	152.	228.	75.9	152.	228.
	1000 tons per yr	80.3	161.	241.	80.3	161.	241.
		contact sulfuric acid			Asarco reduction process		
	$ millions	10.0	16.0	21.0	29.0	49.0	67.0
	$ millions per yr	2.13	3.76	4.63	7.3	13.5	19.0
	¢ per lb copper	1.4	1.2	1.0	4.8	4.4	4.2
			sulfuric acid			sulfur	
	1000 tons per yr	312.(3)	624.(3)	936.(3)	102.	204.	306.
	$ per ton	6.80	6.00	4.90	71.60	66.20	62.10
gas	percent	83.2	83.2	83.2	83.2	83.2	83.2
		limestone slurry scrubbing			limestone slurry scrubbing		
	$ millions	.64	1.10	1.49	.64	1.10	1.49
	$ millions per yr	.38	.63	.87	.38	.63	.87
	¢ per lb copper	.3	.2	.2	.3	.2	.2
			waste			waste	
	1000 tons per yr	45.	91.	136.	45.	91.	136.
gas	percent	8.1	8.1	8.1	8.1	8.1	8.1
	$ millions	10.64	17.10	22.49	29.64	50.10	68.49
	$ millions per yr	2.51	4.39	5.50	7.7	14.1	19.9
	¢ per lb copper	1.7	1.4	1.2	5.1	4.6	4.4
k	1000 tons per yr	7.	14.	21.	7.	14.	21.
	percent	91.3	91.3	91.3	91.3	91.3	91.3

B.

RESULTS OF MATCHING CONTROL S

	Units			
Scheme number		1		
Plant size		small	medium	large
Zinc production	1000 tons per yr	56.6	113.	170.
Sulfur equivalent in offgases	1000 tons per yr	30.3	60.6	90.9
Control process used:		sulfuric acid		
Capital cost	$ millions	2.1	3.7	5.2
Operating cost, gross	$ millions per yr	.51	.90	1.25
	¢ per lb zinc	.45	.39	.36
Byproduct		sulfuric acid (1)		
Production	1000 tons per yr	86.	172.	258.
Cost to produce	$ per ton	5.90	5.20	4.80
Sulfur equivalent lost to stack	1000 tons per yr	2.2	4.4	6.6
Overall sulfur recovery	percent	93.	93.	93.

(1) Sulfuric acid is 66° Baume strength. Equivalent tonnage of 100% acid is given.

A.

Appendix C
Table C - 7

TCHING CONTROL SCHEMES WITH ZINC MODEL A

			2			3			4	
m	large	small	medium	large	small	medium	large	small	medium	large
	170.	56.6	113.	170.	56.6	113.	170.	56.6	113.	170.
	90.9	30.3	60.6	90.9	30.3	60.6	90.9	30.3	60.6	90.9
acid		Asarco reduction process			lime slurry scrubbing			limestone slurry scrubbing		
	5.2	6.3	11.0	15.5	2.2	3.6	5.2	1.01	1.7	2.3
0	1.25	1.45	2.6	3.9	1.18	2.21	3.2	.91	1.63	2.31
9	.36	1.28	1.15	1.14	1.04	.97	.94	.80	.72	.67
acid (1)			sulfur			waste			waste	
	258.	28.	56.	84.	132.	264.	397.	168.	337.	505.
0	4.80	51.80	46.40	46.40						
	6.6	2.2	4.4	6.6	3.7	7.4	11.1	6.6	13.3	19.9
	93.	93.	93.	93.	88.	88.	88.	78.	78.	78.

onnage

Note:

These costs apply only to the specific conditions of zinc smelter model A as described in Table C - 1 and Plate C - 4.

All tons are short tons of 2000 pounds.

B.

RESULTS OF MATCHING CONTROL SCHEMES WITH ZINC

	Units	5
Scheme number		5
Plant size		small
Zinc production	1000 tons per yr	56.6
Sulfur equivalent in offgases	1000 tons per yr	30.5
Control process used:		Cominco absorption; sulfuric acid
Capital cost	$ millions	19.9
Operating cost, gross	$ millions per yr	5.21(1)
	¢ per lb zinc	4.6
Byproduct No. 1		ammonium sulfate
Production	1000 tons per yr	63.
Byproduct No. 2		sulfuric acid
Production	1000 tons per yr	35.(2,3)
Sulfur equivalent lost to stack	1000 tons per yr	3.0
Overall sulfur recovery	percent	90.

(1) Gross cost from graphs of Section VIII c, with credit to acid plant at $7

(2) This is net production after allowance for acid used by the Cominco unit.

(3) Sulfuric acid is 66° Baume strength. Equivalent tonnage of 100% acid is

Note:

These costs apply only to the specific conditions of zinc smelter model B as
Offgases from roasting and sintering are the only offgases considered.

All tons are short tons of 2000 pounds.

A.

Appendix C
Table C - 8

RESULTS OF MATCHING CONTROL SCHEMES WITH ZINC MODEL B

	Units	5 small	6 small	7 small	8 small
	1000 tons per yr	56.6	56.6	56.6	56.6
es	1000 tons per yr	30.5	30.5	30.5	30.5
		Cominco absorption; sulfuric acid	Cominco absorption; Asarco reduction	lime slurry scrubbing	limestone slurry scrubbing
	$ millions	19.9	23.9	3.0	2.0
	$ millions per yr	5.21(1)	6.3	1.37	1.06
	¢ per lb zinc	4.6	5.6	1.21	.93
		ammonium sulfate	ammonium sulfate	waste	waste
	1000 tons per yr	63.	69.	132.	169.
		sulfuric acid	sulfur		
	1000 tons per yr	35.(2,3)	27.		
tack	1000 tons per yr	3.0	3.2	3.2	6.4
	percent	90.	90.	90.	80.

of Section VIII c, with credit to acid plant at $7 per ton for acid used by Cominco unit.

after allowance for acid used by the Cominco unit.

ume strength. Equivalent tonnage of 100% acid is given.

he specific conditions of zinc smelter model B as described in Table C - 1.
intering are the only offgases considered.

000 pounds.

B.

RESULTS OF MATCHING CONTROL SCHEMES WITH

	Units	
Scheme number		9
Plant size		medium
Zinc production	1000 tons per yr	113.
Sulfur equivalent in offgases	1000 tons per yr	60.
Control process used:		Cominco absorption; sulfuric acid
Capital cost	$ millions	36.3
Operating cost, gross	$ millions per yr	10.0(1)
	¢ per lb zinc	4.4
Byproduct No. 1		ammonium sulfate
Production	1000 tons per yr	136.
Byproduct No. 2		sulfuric acid
Production	1000 tons per yr	60.(2,3)
Sulfur equivalent lost to stack	1000 tons per yr	6.3
Overall sulfur recovery	percent	90.

(1) Gross cost from graphs of Section VIII c, with credit to acid plant at

(2) This is net production after allowance for acid used by Cominco unit.

(3) Sulfuric acid is 66° Baume strength. Equivalent tonnage of 100% acid i

Note:

These costs apply only to the specific conditions of zinc smelter model C as
Offgases from the roaster are the only offgases considered.

All tons are short tons of 2000 pounds.

A.

Appendix C
Table C-9

RESULTS OF MATCHING CONTROL SCHEMES WITH ZINC MODEL C

	Units	9 medium	10 medium	11 medium	12 medium
	1000 tons per yr	113.	113.	113.	113.
gases	1000 tons per yr	60.	60.	60.	60.
		Cominco absorption; sulfuric acid	Cominco absorption; Asarco reduction	lime slurry scrubbing	limestone slurry scrubbing
	$ millions	36.3	44.0	5.3	3.35
	$ millions per yr	10.0(1)	12.3	2.4	1.98
	¢ per lb zinc	4.4	5.4	1.06	.88
		ammonium sulfate	ammonium sulfate	waste	waste
	1000 tons per yr	136.	136.	262.	335.
		sulfuric acid	sulfur		
	1000 tons per yr	60.(2,3)	54.		
stack	1000 tons per yr	6.3	6.3	6.4	12.7
	percent	90.	90.	90.	80.

hs of Section VIII c, with credit to acid plant at $7 per ton for acid used by Cominco unit.

on after allowance for acid used by Cominco unit.

Baume strength. Equivalent tonnage of 100% acid is given.

the specific conditions of zinc smelter model C as described in Table C-1.
are the only offgases considered.

f 2000 pounds.

B.

RESULTS OF MATCHING CONTROL SCHEMES WITH ZINC M

	Units		
Scheme number		13	14
Plant size		medium	medium
Zinc production	1000 tons per yr	113.	113.
Sulfur equivalent in offgas	1000 tons per yr	61.2	61.2
Control process used:		Cominco absorption; sulfuric acid	Cominco absorptio Asarco reduction
Capital cost	$ millions	25.3	33.5
Operating cost, gross	$ millions per yr	7.0(1)	9.4
	¢ per lb zinc	3.1	4.15
Byproduct No. 1		ammonium sulfate	ammonium sulfate
Production	1000 tons per yr	138.	138.
Cost to produce	$ per ton		
Byproduct No. 2		sulfuric acid	sulfur
Production	1000 tons per yr	61.(2,3)	55.
Sulfur equivalent lost to stack	1000 tons per yr	6.3	6.3
Overall sulfur recovery	percent	90.	90.

(1) Gross cost from graphs of Section VIII c, with credit to ac
$7 per ton for acid used by Cominco unit.

(2) This is net production after allowance for acid used by Com

(3) Sulfuric acid is 66° Baume strength. Equivalent tonnage of
is given.

Note:

These costs apply only to the specific conditions of zinc m
described in Table C-1. Offgases from sintering machines
offgases considered.

All tons are short tons of 2000 pounds.

A.

Appendix C
Table C - 10

ULTS OF MATCHING CONTROL SCHEMES WITH ZINC MODEL D

	13	14	15	16	17
	medium	medium	medium	medium	medium
er yr	113.	113.	113.	113.	113.
er yr	61.2	61.2	61.2	61.2	61.2
	Cominco absorption; sulfuric acid	Cominco absorption; Asarco reduction	lime slurry scrubbing	limestone slurry scrubbing	sulfuric acid
	25.3	33.5	4.21	2.31	9.8
per yr	7.0(1)	9.4	2.4	1.75	2.7
nc	3.1	4.15	1.06	.77	1.2
	ammonium sulfate	ammonium sulfate	waste	waste	sulfuric acid
er yr	138.	138.	266.	340.	178.(3)
					15.20
	sulfuric acid	sulfur			
er yr	61.(2,3)	55.			
er yr	6.3	6.3	6.5	13.0	3.1
	90.	90.	90.	80.	95.

graphs of Section VIII c, with credit to acid plant at
acid used by Cominco unit.

duction after allowance for acid used by Cominco unit.

s 66° Baume strength. Equivalent tonnage of 100% acid

ly only to the specific conditions of zinc model D as
ble C - 1. Offgases from sintering machines are the only
ered.

ort tons of 2000 pounds.

B.

RESULTS OF MATCHING CONTROL SCHEMES

	Units				
Scheme number			1		
Plant size		small	medium	large	small
Lead production	1000 tons per yr	47.2	94.4	189.	47.2
Sulfur equivalent in offgas	1000 tons per yr	11.5	23.0	46.	11.5
Control process used:			sulfuric acid		Asa
Capital cost	$ millions	1.3	2.1	3.8	3.7
Operating cost, gross	$ millions per yr	.35	.58	.96	.88
	¢ per lb lead	.35	.29	.24	.88
Byproduct			sulfuric acid (1)		
Production	1000 tons per yr	32.9	65.9	132.	10.8
Cost to produce	$ per ton	10.60	8.80	7.30	81.50
Sulfur equivalent lost to stack	1000 tons per yr	.8	1.6	3.2	.8
Overall sulfur recovery	percent	93.	93.	93.	93.

(1) Sulfuric acid is 66° Baume strength. E

Note:

These costs apply only to the specific
described in Table C-1 and the text.

All tons are short tons of 2000 pounds.

A.

Appendix C
Table C - 11

NING CONTROL SCHEMES WITH LEAD MODEL A

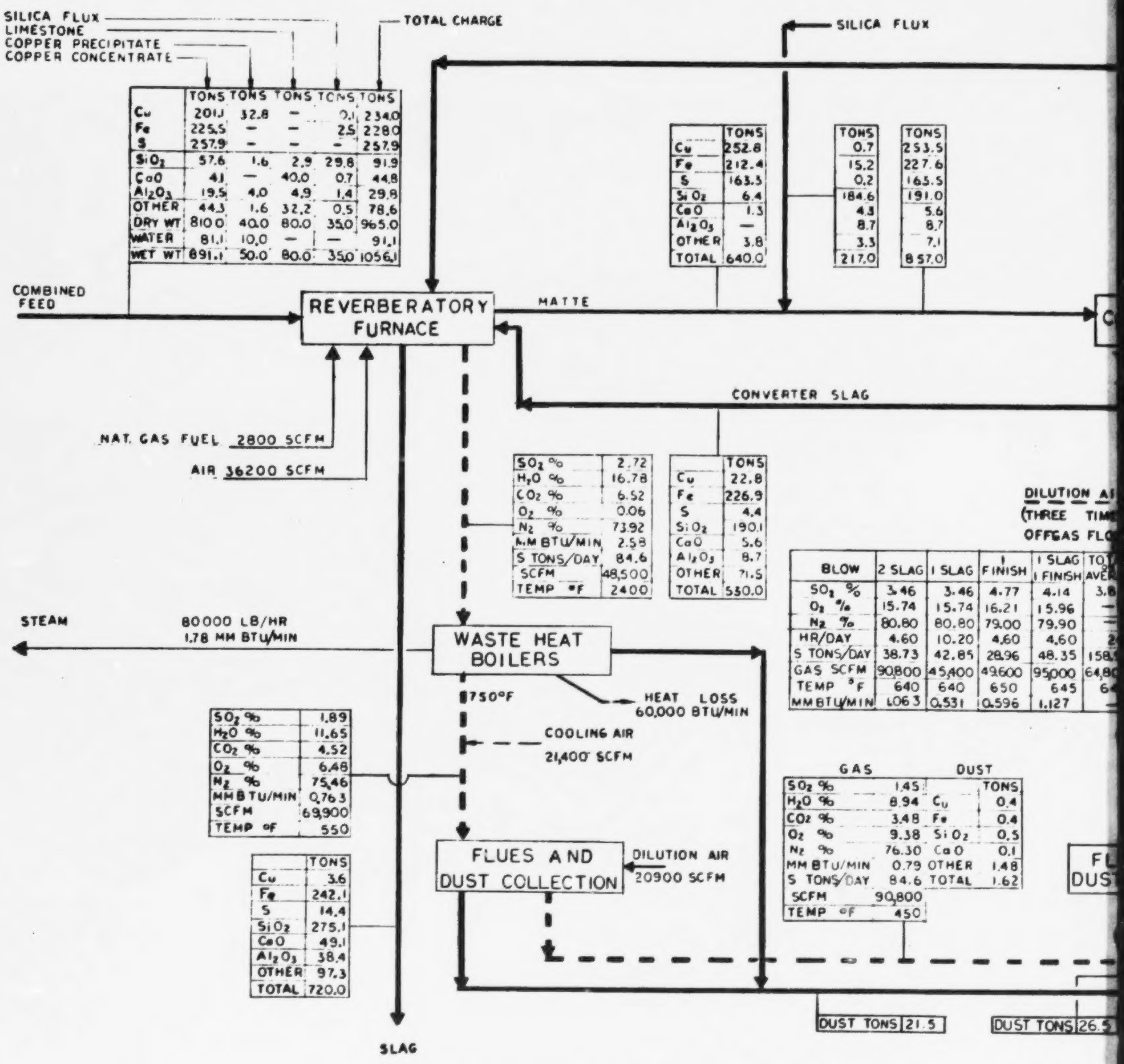
	2			3			4		
large	small	medium	large	small	medium	large	small	medium	large
189.	47.2	94.4	189.	47.2	94.4	189.	47.2	94.4	189.
46.	11.5	23.0	46.	11.5	23.0	46.	11.5	23.0	46.
d		Asarco reduction			lime slurry scrubbing			limestone slurry scrubbing	
3.8	3.7	6.5	11.5	1.4	1.94	3.07	.51	.88	1.50
.96	.88	1.5	2.7	.66	.99	1.73	.54	.75	1.35
.24	.88	.75	.68	.66	.50	.46	.54	.38	.34
(1)		sulfur			waste			waste	
132.	10.8	21.5	43.0	49.	99.	198.	63.	126.	252.
7.30	81.50	70.00	62.80						
3.2	.8	1.6	3.2	1.4	2.7	5.5	2.5	5.0	10.0
93.	93.	93.	93.	88.	88.	88.	78.	78.	78.

6° Baume strength. Equivalent tonnage of 100% acid is given.

only to the specific conditions of lead smelter model A as
C - 1 and the text.

tons of 2000 pounds.

B.


SILICA FLUX
LIMESTONE
COPPER PRECIPITATE
COPPER CONCENTRATE
TOTAL CHARGE
COMBINED FEED
REVERBERATORY FURNACE
MATTE
SILICA FLUX
CONVERTER SLAG
NAT. GAS FUEL 2800 SCFM
AIR 36200 SCFM
STEAM
80000 LB/HR
1.78 MM BTU/MIN
WASTE HEAT BOILERS
750°F
HEAT LOSS 60,000 BTU/MIN
COOLING AIR 21,400 SCFM
FLUES AND DUST COLLECTION
DILUTION AIR 20900 SCFM
SLAG
DILUTION AI
(THREE TIM
OFFGAS FLO
FL
DUST
DUST TONS 21.5
DUST TONS 26.5

	TONS	TONS	TONS	TONS	TONS
Cu	201.1	32.8	—	0.1	234.0
Fe	225.5	—	—	2.5	228.0
S	257.9	—	—	—	257.9
SiO_2	57.6	1.6	2.9	29.8	91.9
CaO	4.1	—	40.0	0.7	44.8
Al_2O_3	19.5	4.0	4.9	1.4	29.8
OTHER	44.3	1.6	32.2	0.5	78.6
DRY WT	810.0	40.0	80.0	35.0	965.0
WATER	81.1	10.0	—	—	91.1
WET WT	891.1	50.0	80.0	35.0	1056.1

	TONS
Cu	252.8
Fe	212.4
S	163.3
SiO_2	6.4
CaO	1.3
Al_2O_3	—
OTHER	3.8
TOTAL	640.0

TONS
0.7
15.2
0.2
184.6
4.3
8.7
3.3
217.0

TONS
253.5
227.6
163.5
191.0
5.6
8.7
7.1
857.0

SO_2 %	2.72
H_2O %	16.78
CO_2 %	6.52
O_2 %	0.06
N_2 %	73.92
MM BTU/MIN	2.58
S TONS/DAY	84.6
SCFM	48,500
TEMP °F	2400

	TONS
Cu	22.8
Fe	226.9
S	4.4
SiO_2	190.1
CaO	5.6
Al_2O_3	8.7
OTHER	71.5
TOTAL	530.0

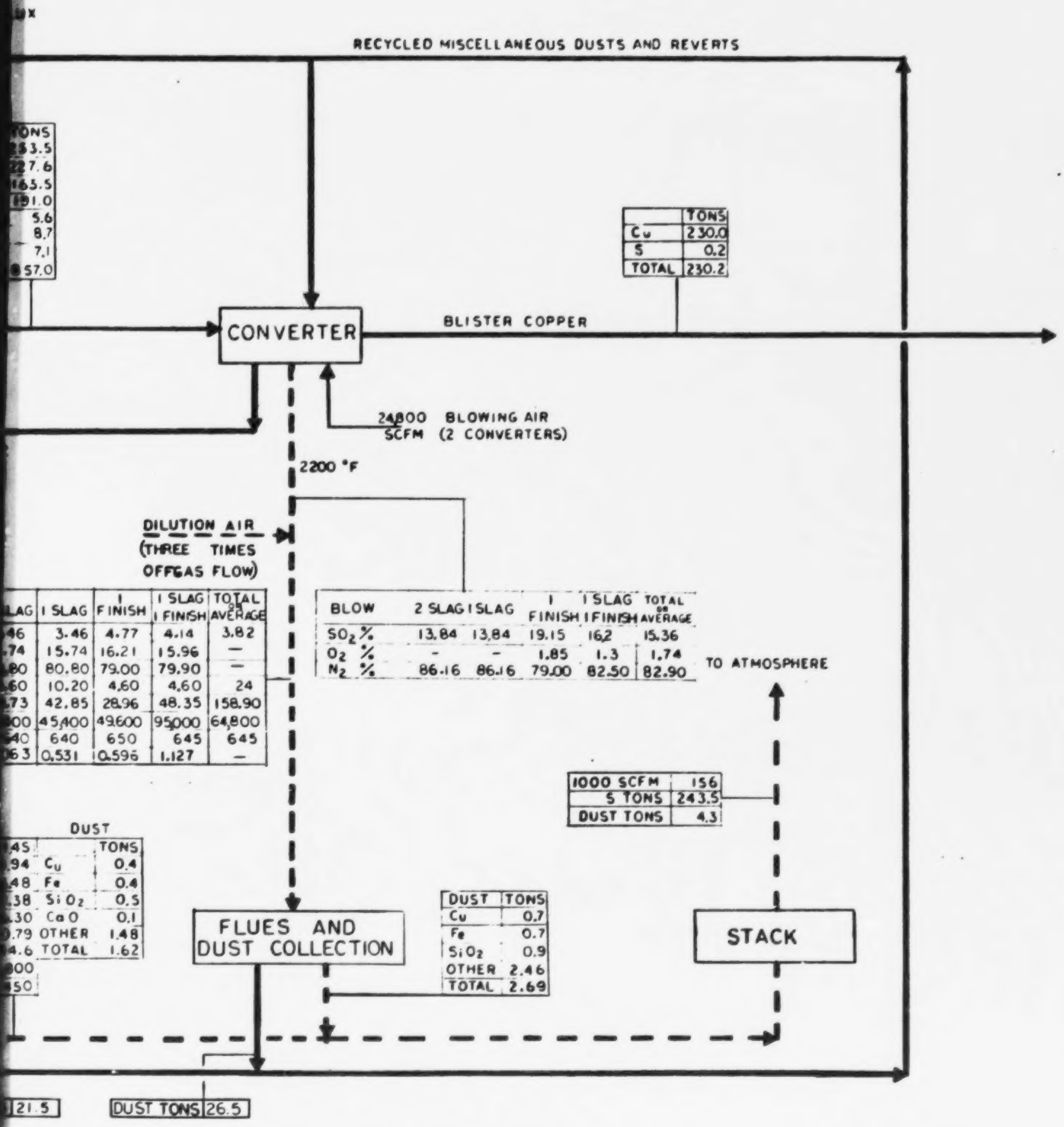
BLOW	2 SLAG	1 SLAG	1 FINISH	1 SLAG 1 FINISH	TOT AVER
SO_2 %	3.46	3.46	4.77	4.14	3.8
O_2 %	15.74	15.74	16.21	15.96	—
N_2 %	80.80	80.80	79.00	79.90	—
HR/DAY	4.60	10.20	4.60	4.60	2
S TONS/DAY	38.73	42.85	28.96	48.35	158.
GAS SCFM	90,800	45,400	49,600	95,000	64,8
TEMP °F	640	640	650	645	6
MMBTU/MIN	1.063	0.531	0.596	1.127	—

SO_2 %	1.89
H_2O %	11.65
CO_2 %	4.52
O_2 %	6.48
N_2 %	75.46
MMBTU/MIN	0.763
SCFM	69,900
TEMP °F	550

	TONS
Cu	3.6
Fe	242.1
S	14.4
SiO_2	275.1
CaO	49.1
Al_2O_3	38.4
OTHER	97.3
TOTAL	720.0

GAS		DUST	TONS
SO_2 %	1.45		
H_2O %	8.94	Cu	0.4
CO_2 %	3.48	Fe	0.4
O_2 %	9.38	SiO_2	0.5
N_2 %	76.30	CaO	0.1
MM BTU/MIN	0.79	OTHER	1.48
S TONS/DAY	84.6	TOTAL	1.62
SCFM	90,800		
TEMP °F	450		

A.


UX
RECYCLED MISCELLANEOUS DUSTS AND REVERTS
TONS
253.5
227.6
165.5
191.0
5.6
8.7
7.1
857.0
CONVERTER
BLISTER COPPER
24800 BLOWING AIR SCFM (2 CONVERTERS)
2200 °F
DILUTION AIR (THREE TIMES OFFGAS FLOW)
LAG | 1 SLAG | 1 FINISH | 1 SLAG 1 FINISH | TOTAL OR AVERAGE
46 | 3.46 | 4.77 | 4.14 | 3.82
74 | 15.74 | 16.21 | 15.96 | —
80 | 80.80 | 79.00 | 79.90 | —
60 | 10.20 | 4.60 | 4.60 | 24
73 | 42.85 | 28.96 | 48.35 | 158.90
00 | 45,400 | 49,600 | 95,000 | 64,800
40 | 640 | 650 | 645 | 645
063 | 0.531 | 0.596 | 1.127 | —
TO ATMOSPHERE
DUST
45 | | TONS
94 | Cu | 0.4
48 | Fe | 0.4
38 | SiO2 | 0.5
30 | CaO | 0.1
79 | OTHER | 1.48
4.6 | TOTAL | 1.62
800
550
FLUES AND DUST COLLECTION
STACK
21.5
DUST TONS 26.5

	TONS
Cu	230.0
S	0.2
TOTAL	230.2

BLOW	2 SLAG	1 SLAG	1 FINISH	1 SLAG 1 FINISH	TOTAL OR AVERAGE
SO_2 %	13.84	13.84	19.15	16.2	15.36
O_2 %	-	-	1.85	1.3	1.74
N_2 %	86.16	86.16	79.00	82.50	82.90

1000 SCFM	156
S TONS	243.5
DUST TONS	4.3

DUST	TONS
Cu	0.7
Fe	0.7
SiO_2	0.9
OTHER	2.46
TOTAL	2.69

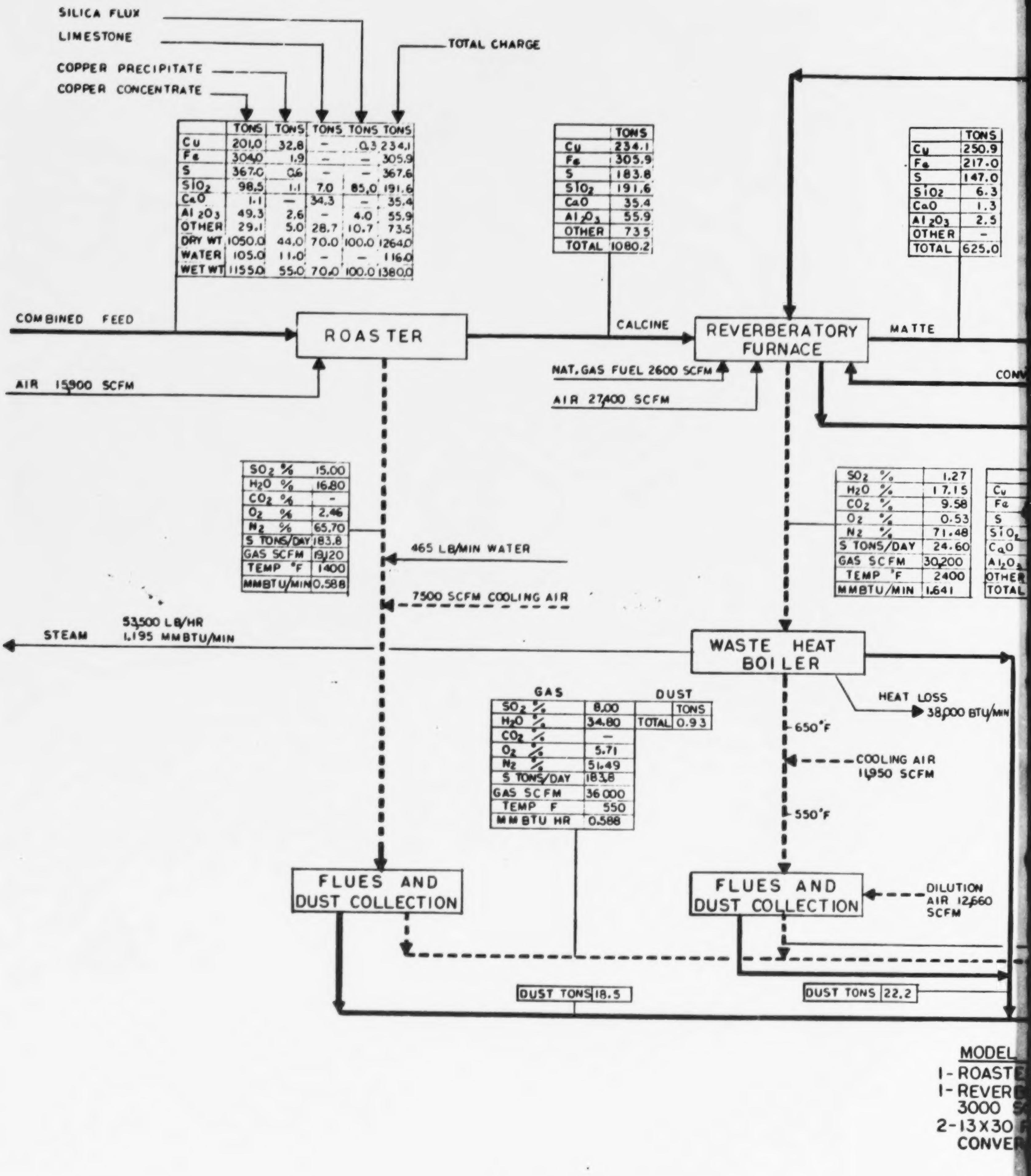
MODEL BASIS
1-REVERBERATORY FURNACE
3000 SQUARE FEET
2-13×30 FT PEIRCE-SMITH
CONVERTERS

KEY:
SOLIDS & LIQUIDS ———
GASES — — —
SCFM MEASURED AT 32°F
AND ONE ATMOSPHERE
MM-MILLION

ALL TONNAGES ARE GIVEN FOR
A 24-HOUR PERIOD IN SHORT TONS

CLIENT NATIONAL AIR POLLUTION CONTROL ADMINISTRATION	ARTHUR G. McKEE & COMPANY WESTERN KNAPP ENGINEERING DIVISION SAN FRANCISCO CALIFORNIA
TITLE COPPER PLANT MODEL -A-	ENG. DEPT. DWG. 10-01-050 PLATE NO. C-1

B.


SILICA FLUX
LIMESTONE
COPPER PRECIPITATE
COPPER CONCENTRATE
TOTAL CHARGE
COMBINED FEED
ROASTER
AIR 15,900 SCFM
CALCINE
REVERBERATORY FURNACE
NAT. GAS FUEL 2600 SCFM
AIR 27,400 SCFM
MATTE
CONV
465 LB/MIN WATER
7500 SCFM COOLING AIR
53,500 LB/HR
1.195 MMBTU/MIN
STEAM
WASTE HEAT BOILER
HEAT LOSS
38,000 BTU/MIN
650°F
COOLING AIR
11,950 SCFM
550°F
FLUES AND DUST COLLECTION
FLUES AND DUST COLLECTION
DILUTION AIR 12,660 SCFM
Cu
Fe
S
SiO2
CaO
Al2O3
OTHER
TOTAL
MODEL
1-ROASTE
1-REVERB
3000 S
2-13X30
CONVER

	TONS	TONS	TONS	TONS	TONS
Cu	201.0	32.8	–	0.3	234.1
Fe	304.0	1.9	–	–	305.9
S	367.0	0.6	–	–	367.6
SiO_2	98.5	1.1	7.0	85.0	191.6
CaO	1.1	—	34.3	–	35.4
Al_2O_3	49.3	2.6	–	4.0	55.9
OTHER	29.1	5.0	28.7	10.7	73.5
DRY WT	1050.0	44.0	70.0	100.0	1264.0
WATER	105.0	11.0	–	–	116.0
WET WT	1155.0	55.0	70.0	100.0	1380.0

	TONS
Cu	234.1
Fe	305.9
S	183.8
SiO_2	191.6
CaO	35.4
Al_2O_3	55.9
OTHER	73.5
TOTAL	1080.2

	TONS
Cu	250.9
Fe	217.0
S	147.0
SiO_2	6.3
CaO	1.3
Al_2O_3	2.5
OTHER	–
TOTAL	625.0

SO_2 %	15.00
H_2O %	16.80
CO_2 %	-
O_2 %	2.46
N_2 %	65.70
S TONS/DAY	183.8
GAS SCFM	19,120
TEMP °F	1400
MMBTU/MIN	0.588

SO_2 %	1.27
H_2O %	17.15
CO_2 %	9.58
O_2 %	0.53
N_2 %	71.48
S TONS/DAY	24.60
GAS SCFM	30,200
TEMP °F	2400
MMBTU/MIN	1.641

GAS

SO_2 %	8.00
H_2O %	34.80
CO_2 %	—
O_2 %	5.71
N_2 %	51.49
S TONS/DAY	183.8
GAS SCFM	36 000
TEMP F	550
MM BTU HR	0.588

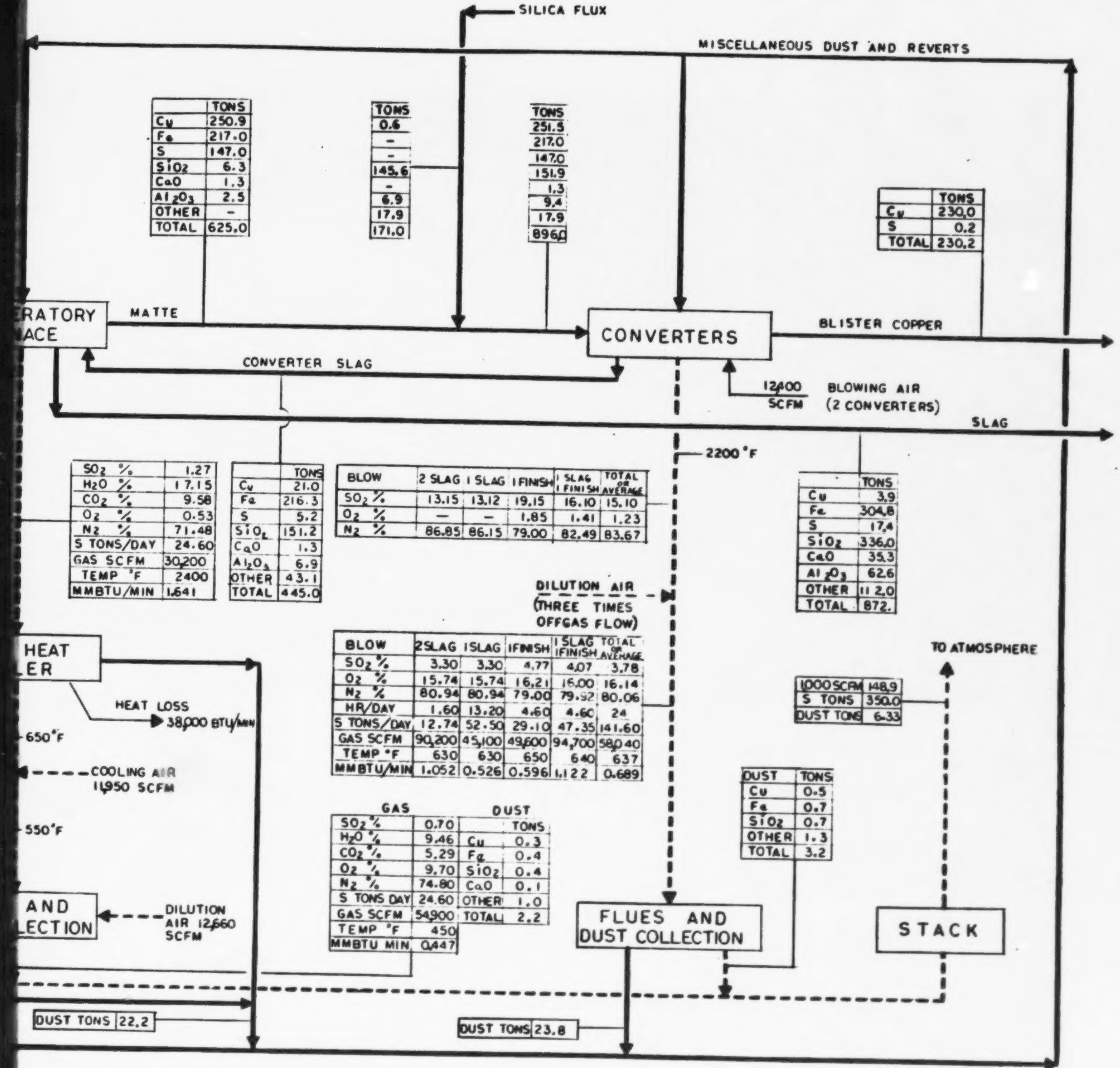
DUST

	TONS
TOTAL	0.93

DUST TONS	18.5

DUST TONS	22.2

A.


SILICA FLUX
MISCELLANEOUS DUST AND REVERTS
ERATORY
NACE
MATTE
CONVERTERS
BLISTER COPPER
CONVERTER SLAG
12,400 SCFM
BLOWING AIR (2 CONVERTERS)
SLAG
2200 °F
DILUTION AIR (THREE TIMES OFFGAS FLOW)
HEAT
LER
HEAT LOSS
38,000 BTU/MIN
650 °F
COOLING AIR 11,950 SCFM
550 °F
AND
LECTION
DILUTION AIR 12,660 SCFM
FLUES AND DUST COLLECTION
STACK
TO ATMOSPHERE

	TONS
Cu	250.9
Fe	217.0
S	147.0
SiO_2	6.3
CaO	1.3
Al_2O_3	2.5
OTHER	-
TOTAL	625.0

TONS
0.6
-
-
145.6
-
6.9
17.9
171.0

TONS
251.5
217.0
147.0
151.9
1.3
9.4
17.9
896.0

	TONS
Cu	230.0
S	0.2
TOTAL	230.2

SO_2 %	1.27
H_2O %	17.15
CO_2 %	9.58
O_2 %	0.53
N_2 %	71.48
S TONS/DAY	24.60
GAS SCFM	30,200
TEMP °F	2400
MMBTU/MIN	1.641

	TONS
Cu	21.0
Fe	216.3
S	5.2
SiO_2	151.2
CaO	1.3
Al_2O_3	6.9
OTHER	43.1
TOTAL	445.0

BLOW	2 SLAG	1 SLAG	1 FINISH	1 SLAG 1 FINISH	TOTAL OR AVERAGE
SO_2 %	13.15	13.12	19.15	16.10	15.10
O_2 %	—	—	1.85	1.41	1.23
N_2 %	86.85	86.15	79.00	82.49	83.67

	TONS
Cu	3.9
Fe	304.8
S	17.4
SiO_2	336.0
CaO	35.3
Al_2O_3	62.6
OTHER	112.0
TOTAL	872.

BLOW	2SLAG	1SLAG	1FINISH	1 SLAG 1FINISH	TOTAL OR AVERAGE
SO_2 %	3.30	3.30	4.77	4.07	3.78
O_2 %	15.74	15.74	16.21	16.00	16.14
N_2 %	80.94	80.94	79.00	79.92	80.06
HR/DAY	1.60	13.20	4.60	4.60	24
S TONS/DAY	12.74	52.50	29.10	47.35	141.60
GAS SCFM	90,200	45,100	49,600	94,700	58,040
TEMP °F	630	630	650	640	637
MMBTU/MIN	1.052	0.526	0.596	1.122	0.689

1000 SCFM	148.9
S TONS	350.0
DUST TONS	6.33

DUST	TONS
Cu	0.5
Fe	0.7
SiO_2	0.7
OTHER	1.3
TOTAL	3.2

GAS

SO_2 %	0.70
H_2O %	9.46
CO_2 %	5.29
O_2 %	9.70
N_2 %	74.80
S TONS DAY	24.60
GAS SCFM	54,900
TEMP °F	450
MMBTU MIN	0.447

DUST

	TONS
Cu	0.3
Fe	0.4
SiO_2	0.4
CaO	0.1
OTHER	1.0
TOTAL	2.2

DUST TONS	22.2

DUST TONS	23.8

MODEL BASIS:

1-ROASTER
1-REVERBERATORY FURNACE
3000 SQUARE FEET
2-13X30 FT PEIRCE-SMITH
CONVERTERS

ALL TONNAGES ARE GIVEN FOR A 24-HOUR PERIOD IN SHORT TONS

KEY:
SOLIDS AND LIQUIDS ———
GASES - - - - - -
SCFM MEASURED AT 32°F AND ONE ATMOSPHERE
MM = MILLION

CLIENT
NATIONAL AIR
POLLUTION CONTROL
ADMINISTRATION

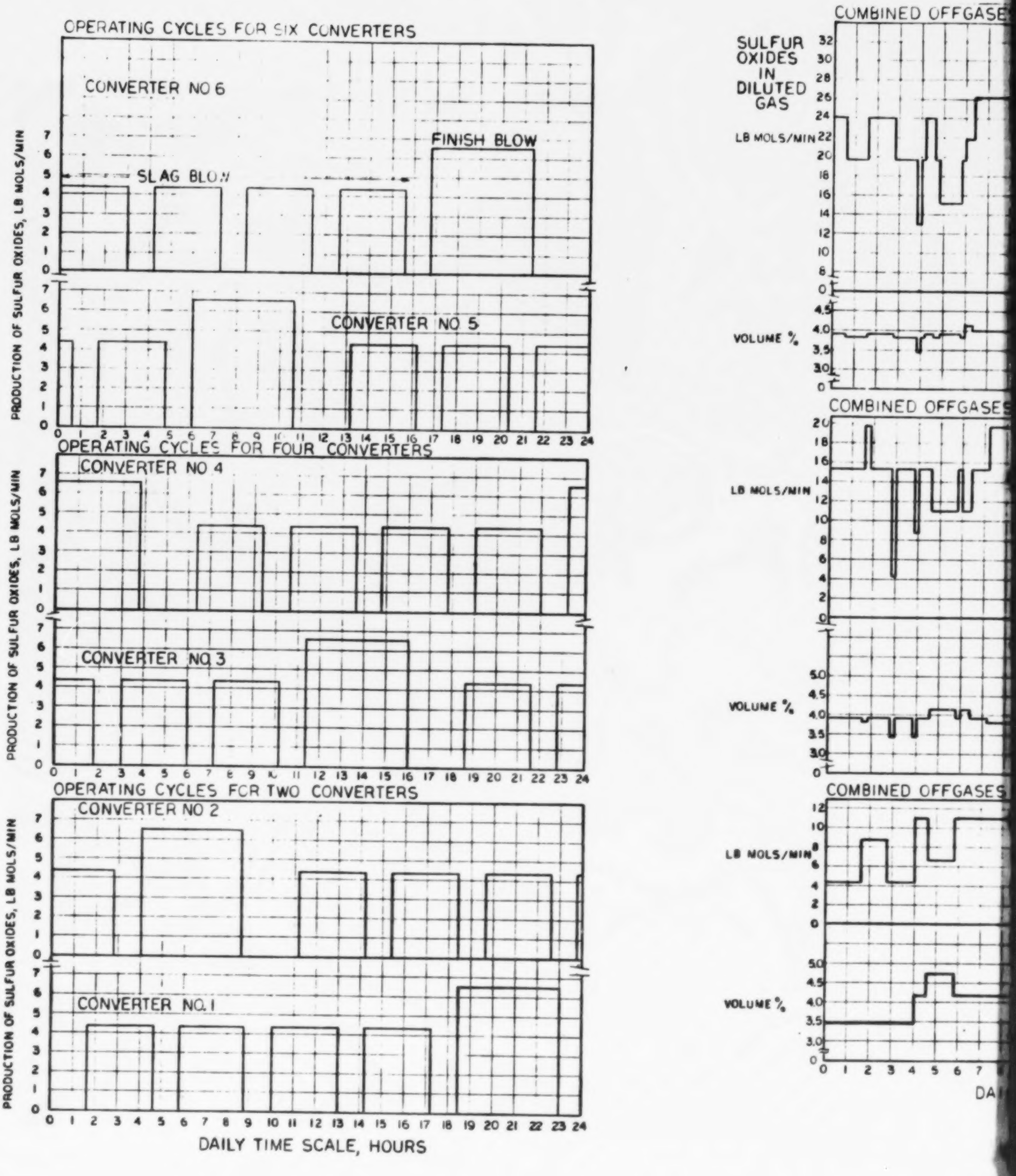
TITLE
COPPER PLANT MODEL
-B-

ARTHUR G. McKEE & COMPANY
WESTERN KNAPP ENGINEERING DIVISION
SAN FRANCISCO CALIFORNIA

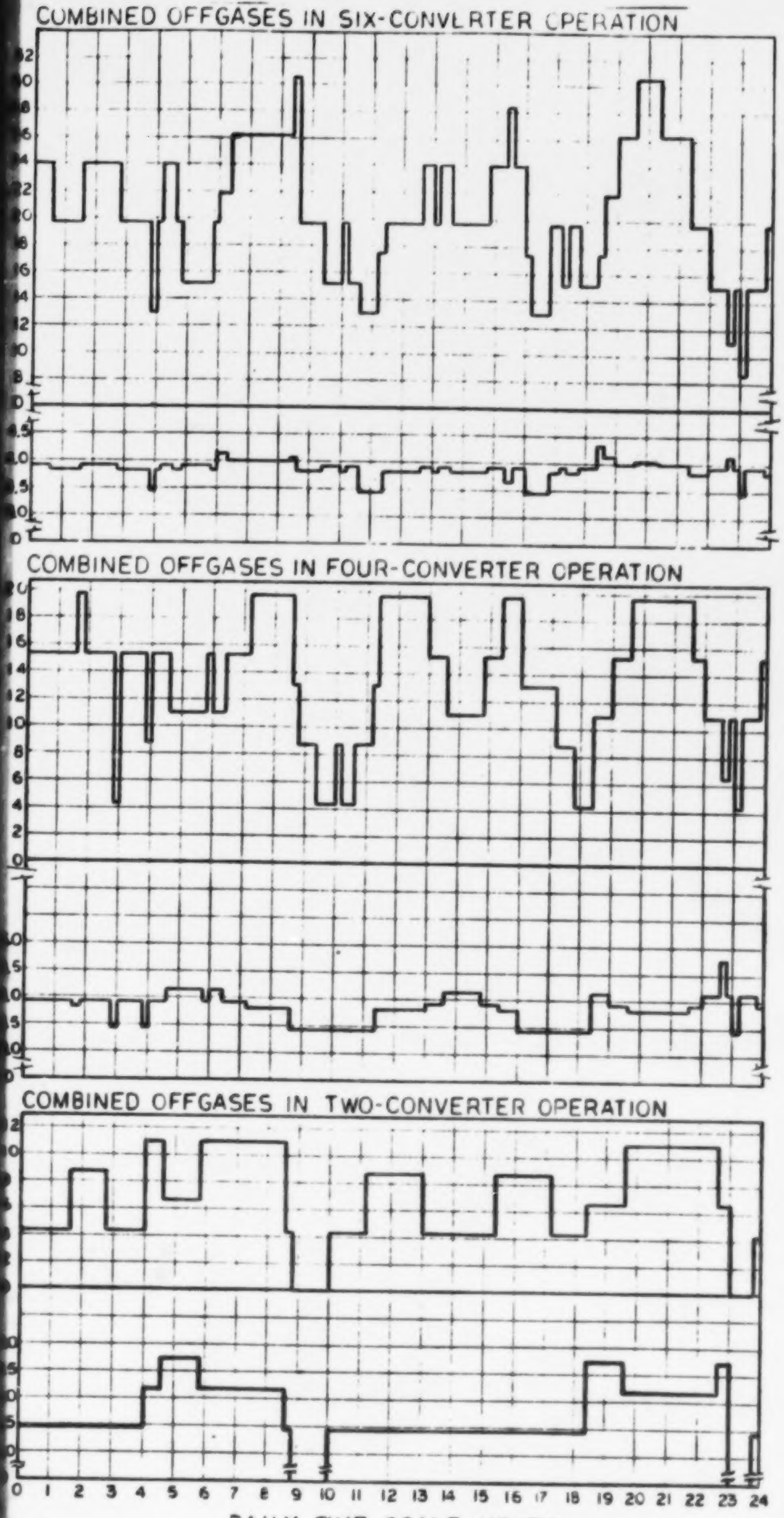
ENG. DEPT. DWG. 10-01-051

PLATE NO. C.2

B.


OPERATING CYCLES FOR SIX CONVERTERS
CONVERTER NO 6
SLAG BLOW
FINISH BLOW
CONVERTER NO 5
PRODUCTION OF SULFUR OXIDES, LB MOLS/MIN
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
OPERATING CYCLES FOR FOUR CONVERTERS
CONVERTER NO 4
CONVERTER NO 3
PRODUCTION OF SULFUR OXIDES, LB MOLS/MIN
OPERATING CYCLES FOR TWO CONVERTERS
CONVERTER NO 2
CONVERTER NO.1
PRODUCTION OF SULFUR OXIDES, LB MOLS/MIN
DAILY TIME SCALE, HOURS
COMBINED OFFGASES
SULFUR OXIDES IN DILUTED GAS
LB MOLS/MIN
VOLUME %
COMBINED OFFGASES
LB MOLS/MIN
VOLUME %
COMBINED OFFGASES
LB MOLS/MIN
VOLUME %
DA

A.


COMBINED OFFGASES IN SIX-CONVERTER OPERATION

COMBINED OFFGASES IN FOUR-CONVERTER OPERATION

COMBINED OFFGASES IN TWO-CONVERTER OPERATION

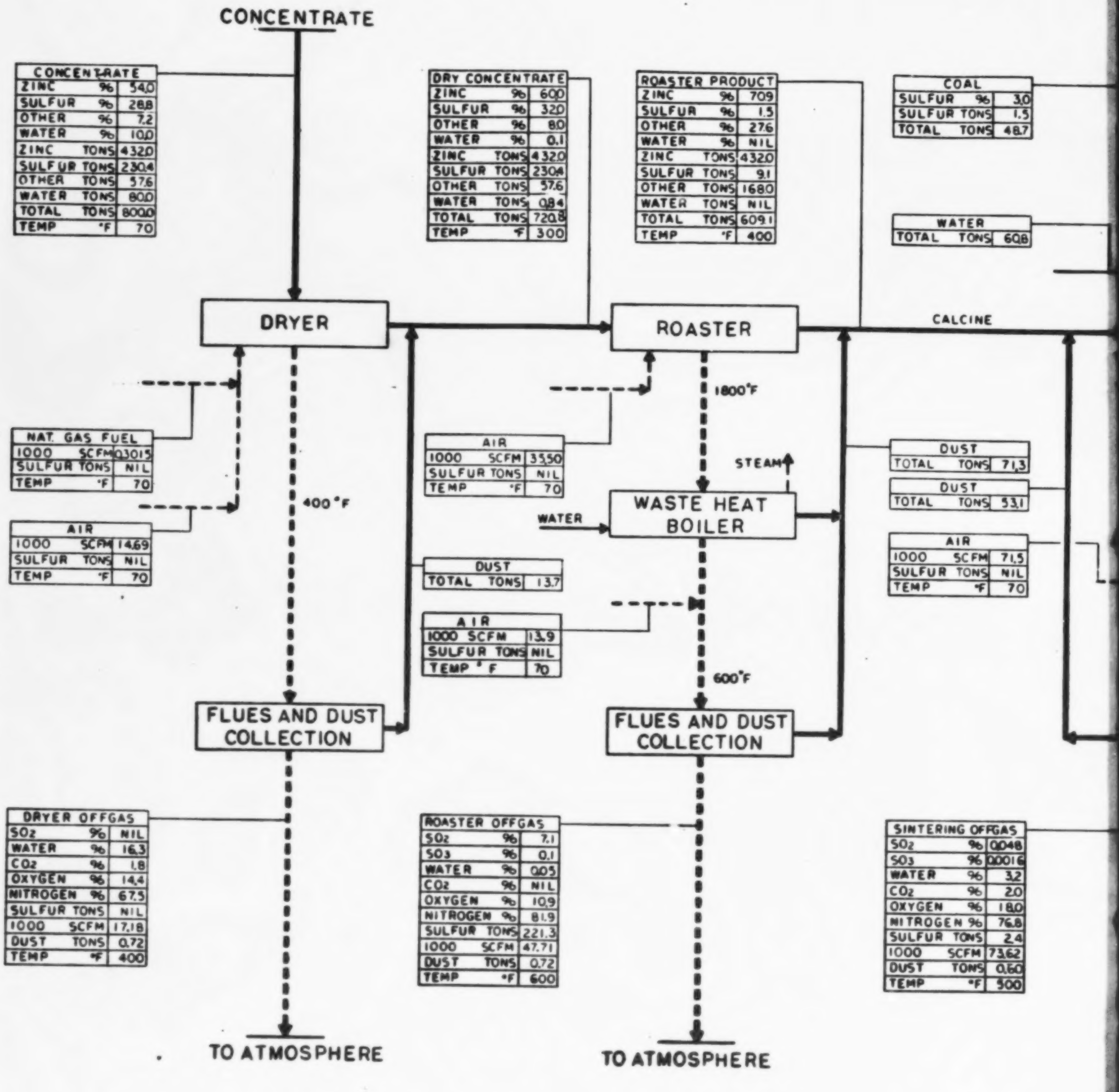
NOTE
THESE ARE IDEALIZED GRAPHS THAT DO NOT SHOW THE MANY SHORT-PERIOD SHUTDOWNS OF THE CONVERTER BLOW FOR VARIOUS PURPOSES

KEY
MIN = MINUTE
SULFUR EQUIVALENT (SHORT TONS/DAY) = 23.09 - LB MOLS/MIN

BASIS: SEE COPPER MODEL A

B.

CLIENT	
NATIONAL AIR POLLUTION CONTROL ADMINISTRATION	ARTHUR G. McKEE & COMPANY WESTERN KNAPP ENGINEERING DIVISION SAN FRANCISCO CALIFORNIA
TITLE	ENG DEPT. DWG 10-01-032
SMELTER PLANT MODELS COPPER CONVERTER CYCLES	PLATE NO. C-3


CONCENTRATE
DRYER
ROASTER
CALCINE
1800°F
STEAM
WATER
WASTE HEAT BOILER
400°F
600°F
FLUES AND DUST COLLECTION
FLUES AND DUST COLLECTION
TO ATMOSPHERE
TO ATMOSPHERE

CONCENTRATE	
ZINC %	54.0
SULFUR %	28.8
OTHER %	7.2
WATER %	10.0
ZINC TONS	432.0
SULFUR TONS	230.4
OTHER TONS	57.6
WATER TONS	80.0
TOTAL TONS	800.0
TEMP °F	70

DRY CONCENTRATE	
ZINC %	60.0
SULFUR %	32.0
OTHER %	8.0
WATER %	0.1
ZINC TONS	432.0
SULFUR TONS	230.4
OTHER TONS	57.6
WATER TONS	0.84
TOTAL TONS	720.8
TEMP °F	300

ROASTER PRODUCT	
ZINC %	70.9
SULFUR %	1.5
OTHER %	27.6
WATER %	NIL
ZINC TONS	432.0
SULFUR TONS	9.1
OTHER TONS	168.0
WATER TONS	NIL
TOTAL TONS	609.1
TEMP °F	400

COAL	
SULFUR %	3.0
SULFUR TONS	1.5
TOTAL TONS	48.7

WATER	
TOTAL TONS	60.8

NAT. GAS FUEL	
1000 SCFM	0.3015
SULFUR TONS	NIL
TEMP °F	70

AIR	
1000 SCFM	14.69
SULFUR TONS	NIL
TEMP °F	70

AIR	
1000 SCFM	35.50
SULFUR TONS	NIL
TEMP °F	70

DUST	
TOTAL TONS	13.7

AIR	
1000 SCFM	13.9
SULFUR TONS	NIL
TEMP °F	70

DUST	
TOTAL TONS	71.3

DUST	
TOTAL TONS	53.1

AIR	
1000 SCFM	71.5
SULFUR TONS	NIL
TEMP °F	70

DRYER OFFGAS	
SO_2 %	NIL
WATER %	16.3
CO_2 %	1.8
OXYGEN %	14.4
NITROGEN %	67.5
SULFUR TONS	NIL
1000 SCFM	17.18
DUST TONS	0.72
TEMP °F	400

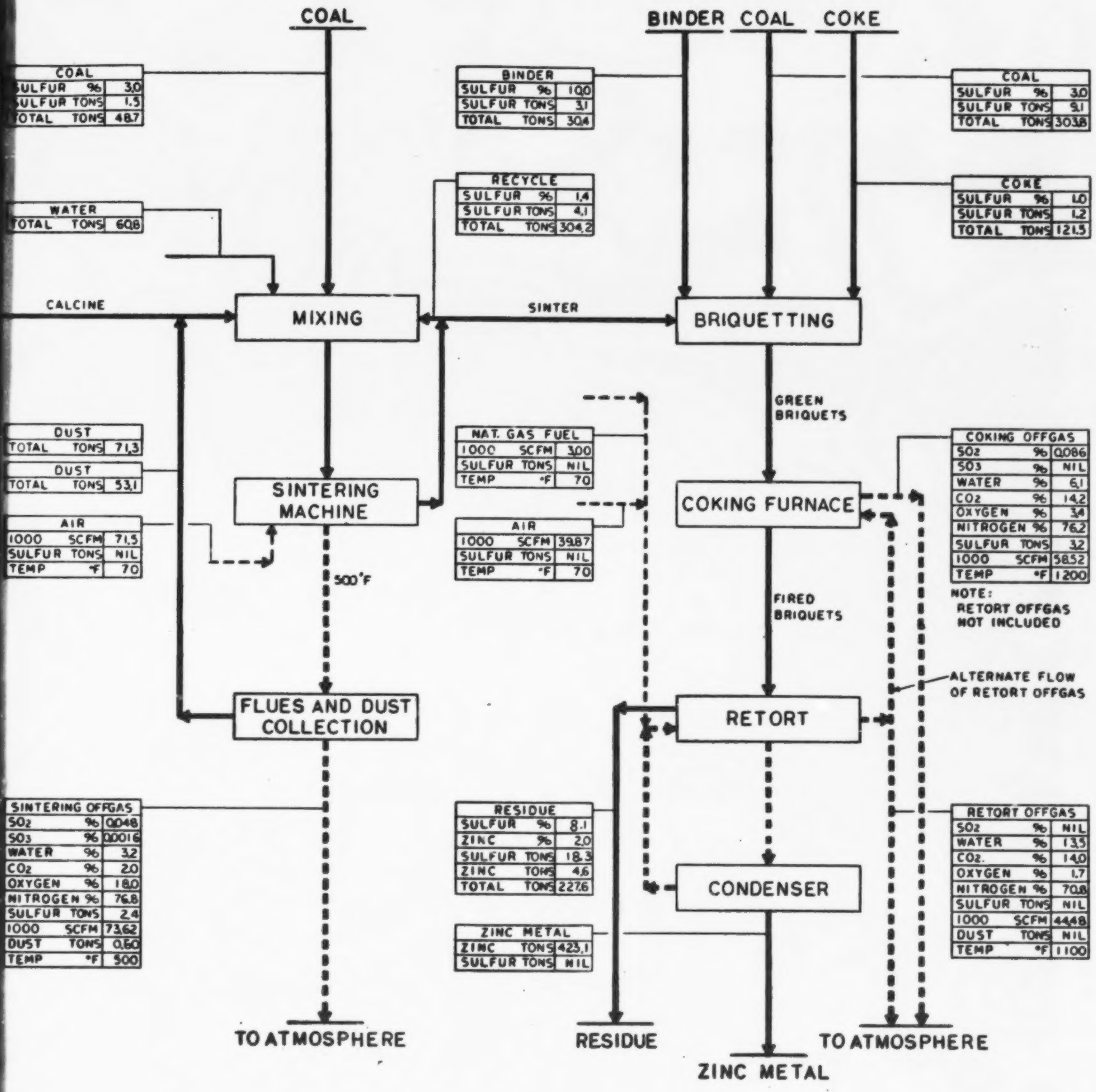
ROASTER OFFGAS	
SO_2 %	7.1
SO_3 %	0.1
WATER %	0.05
CO_2 %	NIL
OXYGEN %	10.9
NITROGEN %	81.9
SULFUR TONS	221.3
1000 SCFM	47.71
DUST TONS	0.72
TEMP °F	600

SINTERING OFFGAS	
SO_2 %	0.048
SO_3 %	0.0016
WATER %	3.2
CO_2 %	2.0
OXYGEN %	18.0
NITROGEN %	76.8
SULFUR TONS	2.4
1000 SCFM	73.62
DUST TONS	0.60
TEMP °F	500

BASIS:
TONNAGES ARE GIVEN
FOR A 24 HOUR PERIOD
IN SHORT TONS

KEY:
SOLIDS & LIQUIDS ————
GASES - - - - - - - -
SCFM MEASURED AT 32 °F AND ONE AT
NIL-NEGLECTED (INSIGNIFICANT QU
AFFECTING MATERIAL BALANCE)

A.


COAL
BINDER
COAL
COKE
CALCINE
MIXING
SINTER
BRIQUETTING
GREEN BRIQUETS
SINTERING MACHINE
500°F
COKING FURNACE
FIRED BRIQUETS
FLUES AND DUST COLLECTION
RETORT
CONDENSER
ALTERNATE FLOW OF RETORT OFFGAS
TO ATMOSPHERE
RESIDUE
ZINC METAL
TO ATMOSPHERE

COAL	
SULFUR %	3.0
SULFUR TONS	1.5
TOTAL TONS	48.7

WATER	
TOTAL TONS	60.8

DUST	
TOTAL TONS	71.3

DUST	
TOTAL TONS	53.1

AIR	
1000 SCFM	71.5
SULFUR TONS	NIL
TEMP °F	70

SINTERING OFFGAS	
SO_2 %	0.048
SO_3 %	0.0016
WATER %	3.2
CO_2 %	2.0
OXYGEN %	18.0
NITROGEN %	76.8
SULFUR TONS	2.4
1000 SCFM	73.62
DUST TONS	0.60
TEMP °F	500

BINDER	
SULFUR %	10.0
SULFUR TONS	3.1
TOTAL TONS	30.4

RECYCLE	
SULFUR %	1.4
SULFUR TONS	4.1
TOTAL TONS	304.2

NAT. GAS FUEL	
1000 SCFM	3.00
SULFUR TONS	NIL
TEMP °F	70

AIR	
1000 SCFM	39.87
SULFUR TONS	NIL
TEMP °F	70

RESIDUE	
SULFUR %	8.1
ZINC %	2.0
SULFUR TONS	18.3
ZINC TONS	4.6
TOTAL TONS	227.6

ZINC METAL	
ZINC TONS	423.1
SULFUR TONS	NIL

COAL	
SULFUR %	3.0
SULFUR TONS	9.1
TOTAL TONS	303.8

COKE	
SULFUR %	1.0
SULFUR TONS	1.2
TOTAL TONS	121.5

COKING OFFGAS	
SO_2 %	0.086
SO_3 %	NIL
WATER %	6.1
CO_2 %	14.2
OXYGEN %	3.4
NITROGEN %	76.2
SULFUR TONS	3.2
1000 SCFM	58.52
TEMP °F	1200

NOTE:
RETORT OFFGAS NOT INCLUDED

RETORT OFFGAS	
SO_2 %	NIL
WATER %	13.5
CO_2. %	14.0
OXYGEN %	1.7
NITROGEN %	70.8
SULFUR TONS	NIL
1000 SCFM	44.48
DUST TONS	NIL
TEMP °F	1100

S ————
- - - - - - - -
AT 32 °F AND ONE ATMOSPHERE
(INSIGNIFICANT QUANTITY NOT
ERIAL BALANCE)

B.

CLIENT NATIONAL AIR POLLUTION CONTROL ADMINISTRATION	ARTHUR G. McKEE & COMPANY WESTERN KNAPP ENGINEERING DIVISION SAN FRANCISCO CALIFORNIA
TITLE MODEL A ZINC PLANT FLOW DIAGRAM	ENG. DEPT. DWG. 10-01-053 PLATE NO. C-4

APPENDIX D

METEOROLOGICAL AND TOPOGRAPHIC FACTORS AFFECTING AIR POLLUTION POTENTIAL OF U.S. NONFERROUS SMELTERS

Smelter Regions . . . . D - 1

Meteorological Parameters . . . . D - 1

Air Pollution Potential of Smelter Regions . . . . D - 18

METEOROLOGICAL AND TOPOGRAPHIC FACTORS AFFECTING AIR POLLUTION POTENTIAL OF U.S. NONFERROUS SMELTERS

Any precise analysis of the air pollution potential of an individual smelter requires meteorological data for the specific smelter site, and such data are in general not publicly available. However, it is possible to make a useful appraisal of the meteorological and the terrain factors that affect the air pollution potential of the general regions of the United States within which smelters are located.

The meteorological variables that can be considered in such an analysis of regional air pollution potentials are inversion frequencies, monthly mean maximum mixing depths (MMD), surface winds, and general airflow conditions. Topography must also be considered because it plays a major role in modifying the influence of the meteorological variables.

Smelter Regions

For the purpose of this analysis the smelters of the U.S. have been grouped into five more or less homogeneous regions. The five regions and the smelter areas included are as follows:

1. Appalachian--Tennessee, West Virginia, Pennsylvania
2. Midwest--Michigan, Illinois, Missouri, Kansas, Oklahoma Texas (Panhandle)
3. Southwestern Desert--Texas (El Paso), New Mexico, Arizona Nevada, Utah
4. Northern Rocky Mountain--Montana, Idaho
5. Pacific Coast--Washington, California

Within each region the meteorological and topographic conditions important to air pollution potential are generally similar from place to place. A more detailed subdivision is probably not warranted except when it is necessary to analyze conditions at individual smelters.

Meteorological Parameters

Four meteorological parameters have been assembled to provide a basis for estimating air pollution potential. These include two parameters related to turbulent diffusion -- inversion frequency and monthly mean MMD; and two factors dealing with wind movement -- mean wind frequencies and general airflow patterns.

Average Inversion Frequency

Inversion frequency is a significant factor in the assessment of air pollution potential because inversions can contribute to the accumulation of pollutants in the source area. Inversions are frequently accompanied by light and variable winds, but turbulent mixing within an inversion layer is at a minimum. The slowness of turbulent mixing can result in an accumulation of pollutants around a source at concentrations that are relatively high compared with those existing under conditions of greater atmospheric turbulence. Under inversion conditions, the effluents emerging from a stack will typically rise to some height above the top of the stack, dependent on the buoyancy of the effluent plume, and then will spread out in a relatively thin layer that will subsequently drift downwind with only very slow breakup or dilution.

Under inversion conditions it is unlikely that the layered plume will contact the ground except in cases where terrain features such as hills or valley sides are high enough to intersect the contaminated layer and the wind pattern is not such as to cause the plume to flow around or over these obstacles. The greatest hazard can arise when turbulence sets in at the ground and reaches up to the height of the effluent layer. The resulting turbulent mixing may bring the accumulated pollutant down to ground level at relatively high concentrations. Even though this phenomenon, termed a "fumigation," usually lasts for only a relatively short time, the high pollutant concentrations may make the exposure damaging to receptors. Fumigations have frequently been the cause of vegetation damage and complaints about air pollution around smelters (e.g., at Trail, B.C.).

The frequency of low-level inversions over the U.S. has been studied by Hosler,[2] who tabulated the frequencies of inversions or isothermal conditions having a base at or below 500 feet above ground level. Hosler used radiosonde temperature and altitude data from the U.S. Weather Bureau's upper-air observation network. The frequency statistics were derived from measurements made at four daily observation times, including both daytime and nighttime. Hosler also included analyses relating inversion frequencies to nighttime surface wind speed and to cloud cover.

The seasonal patterns of inversion frequency derived by Hosler[2] are shown in Figs. D-1 and D-2. Isopleths of the maximum inversion frequency reported at any of the four daily observation times are shown in Figs. D-1A through D-1E. These values show the percentage frequency of nights or days that had at least one hour of inversion. They do not necessarily apply to the same time of day at each station.

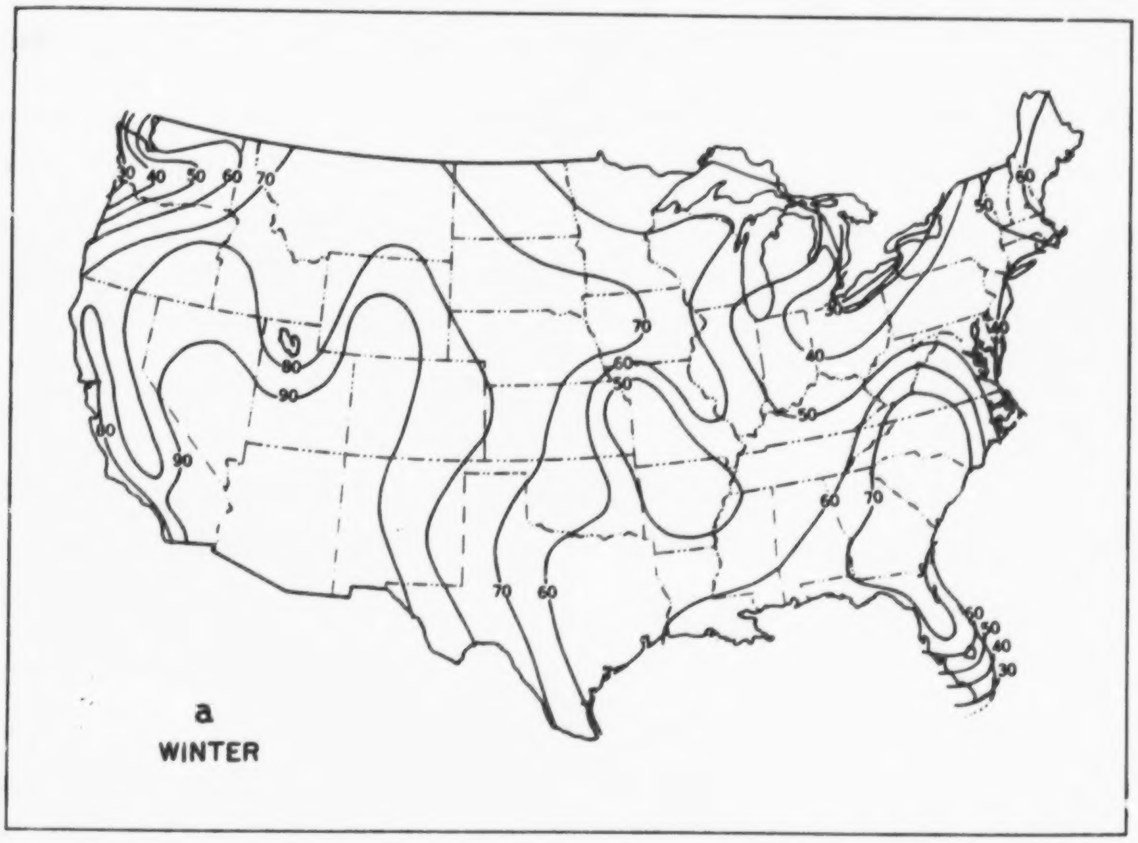
By weighting the percentage frequencies of inversions according to estimated values for the durations of the stable periods, Hosler[2] also obtained estimates of the average inversion frequency -- the percentage of the total hours, seasonal or annual, that inversions or isothermal conditions existed at or below 500 feet. Isopleths of average inversion frequency are shown in Figs. D-2A through D-2E.

From Figs. D-1 and D-2 it can be seen that periods in which stable layers lie close to the ground, which implies limited vertical mixing, can be expected to occur over almost the whole of the contiguous U.S. for 25 percent or more of the time on an annual basis. During the fall and winter months, when radiation cooling is a particularly important factor, low-level stability occurs more than half of the time over much of the Rocky Mountains and Intermountain Plateau regions.

When the annual maximum frequency of low-level inversions is considered, Fig. D-1E shows that low inversions occurred at some time of the day on more than 50% of the days over almost all areas of the U.S. Over large parts of the area west of the Rockies the frequency with which low-level stability was observed at some time during the day ranged between 75% and 90%.

Mixing Depth

The mixing depth is the height of the atmospheric layer within which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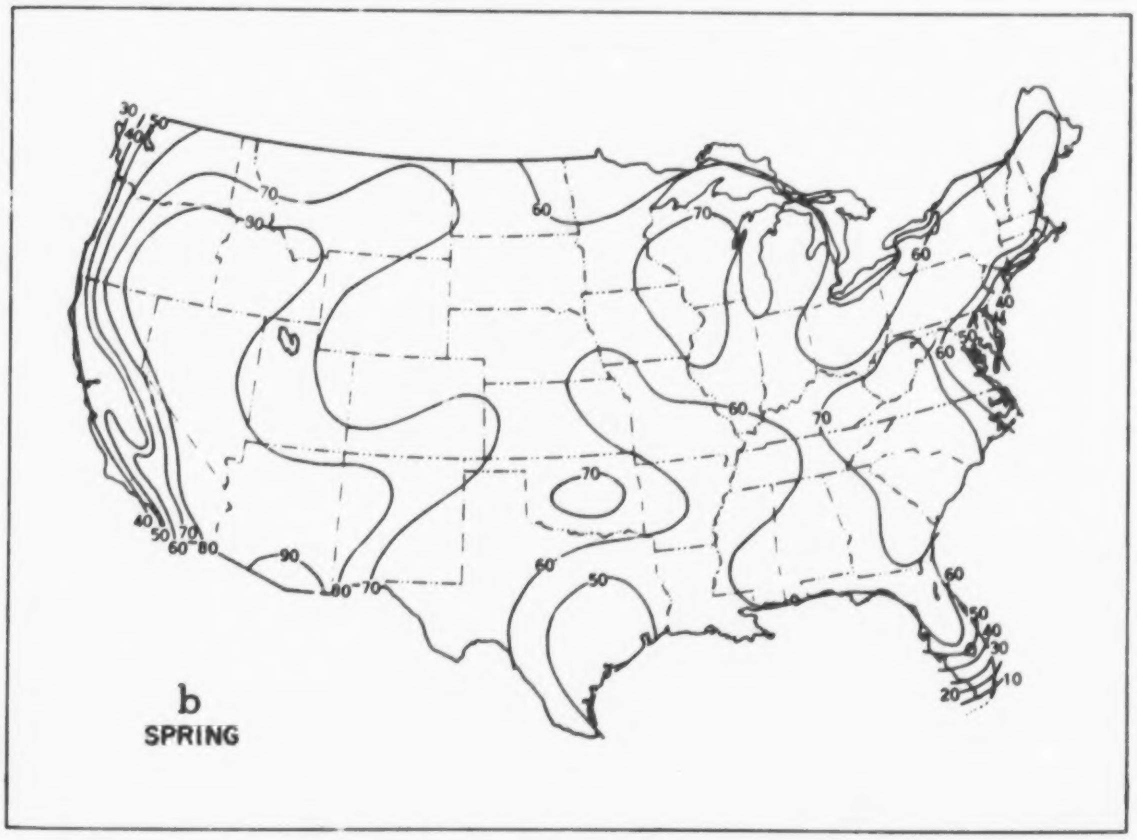
50
60

a
WINTER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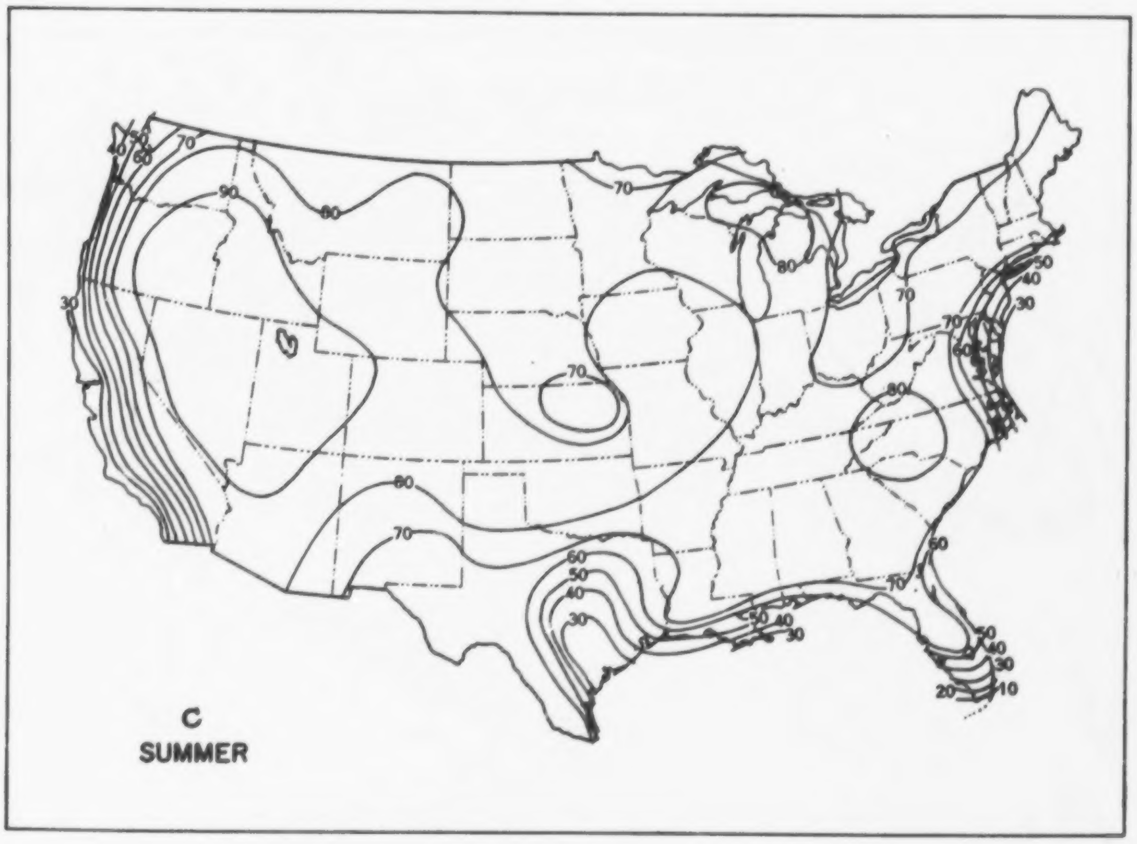
60
50
40
30
20
10

b
SPRING

FIGURE D-1 INVERSION PERCENT FREQUENCY (maximum observed)

SOURCE: Hosler, C. R., Mon. Weather Rev. 89, 319-339 (1961).



c
SUMMER
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90
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80
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50
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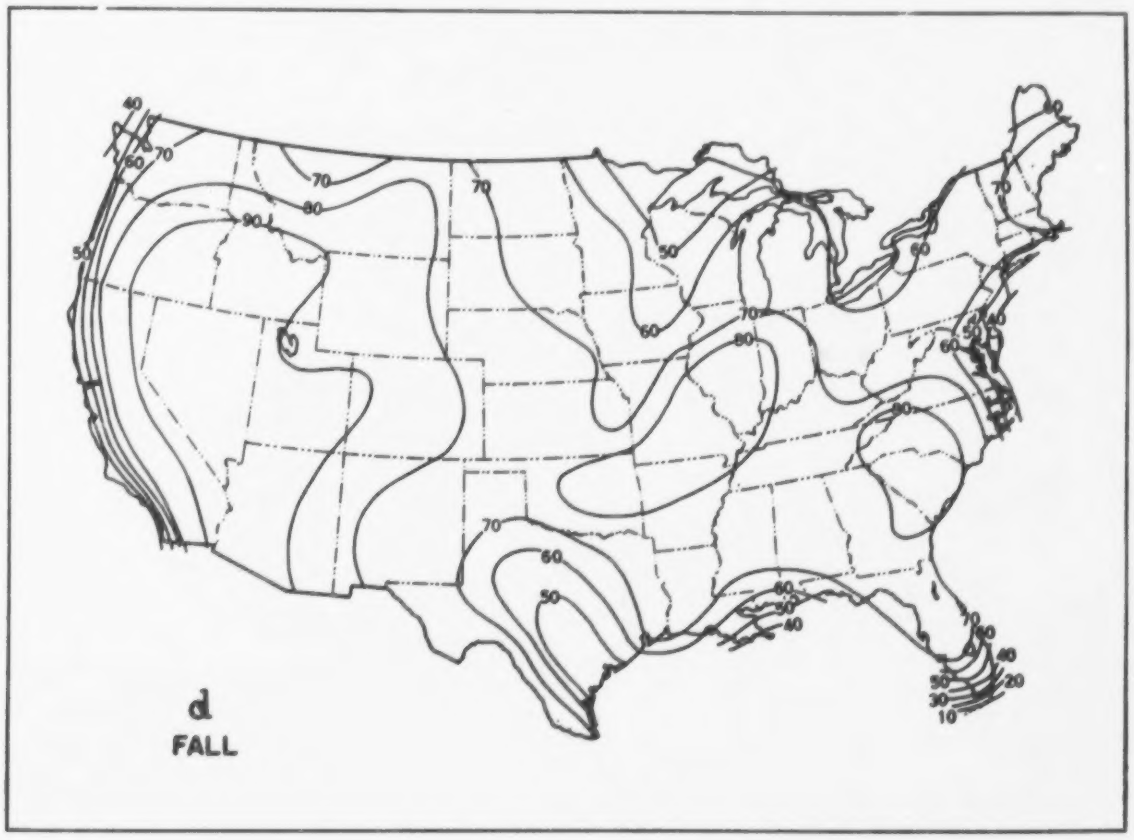
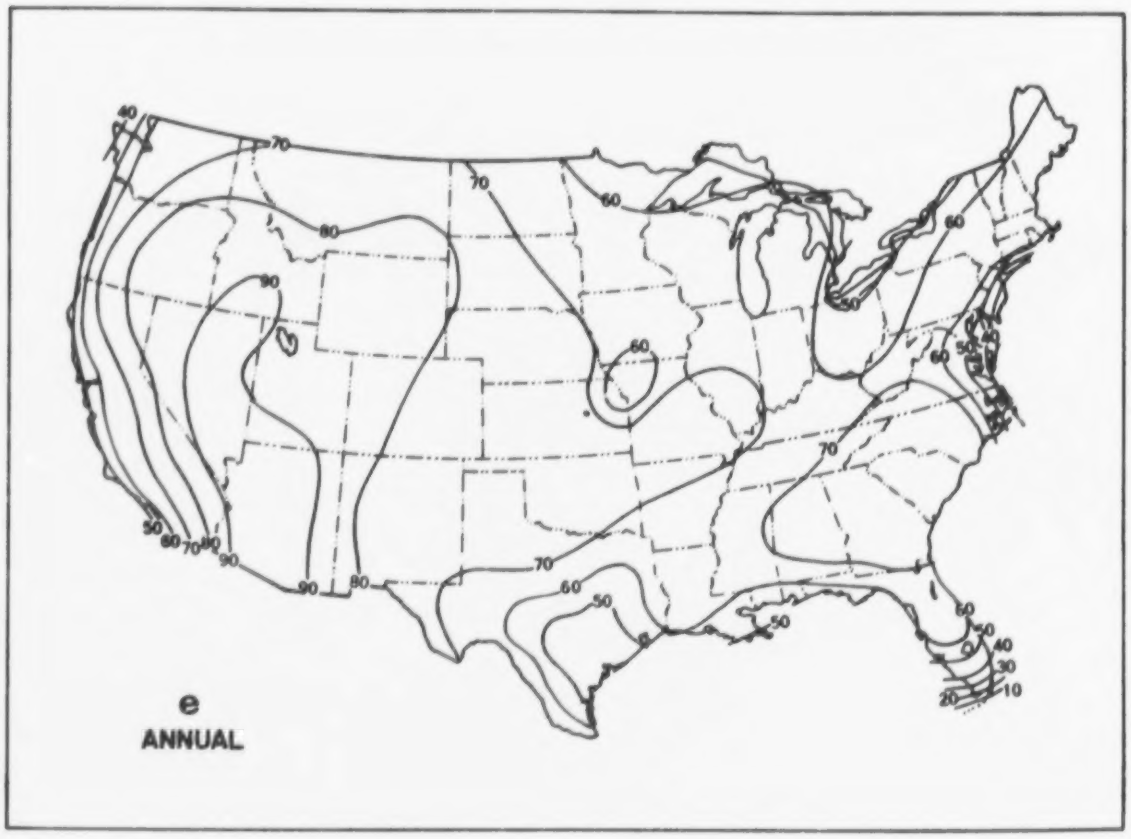
30
60
70
50
40
30
20
10



d
FALL
40
60
70
80
90
50
70
60
50
70
80
60
90
70
60
50
40
20
10

FIGURE D-1 Continued


40
70
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70
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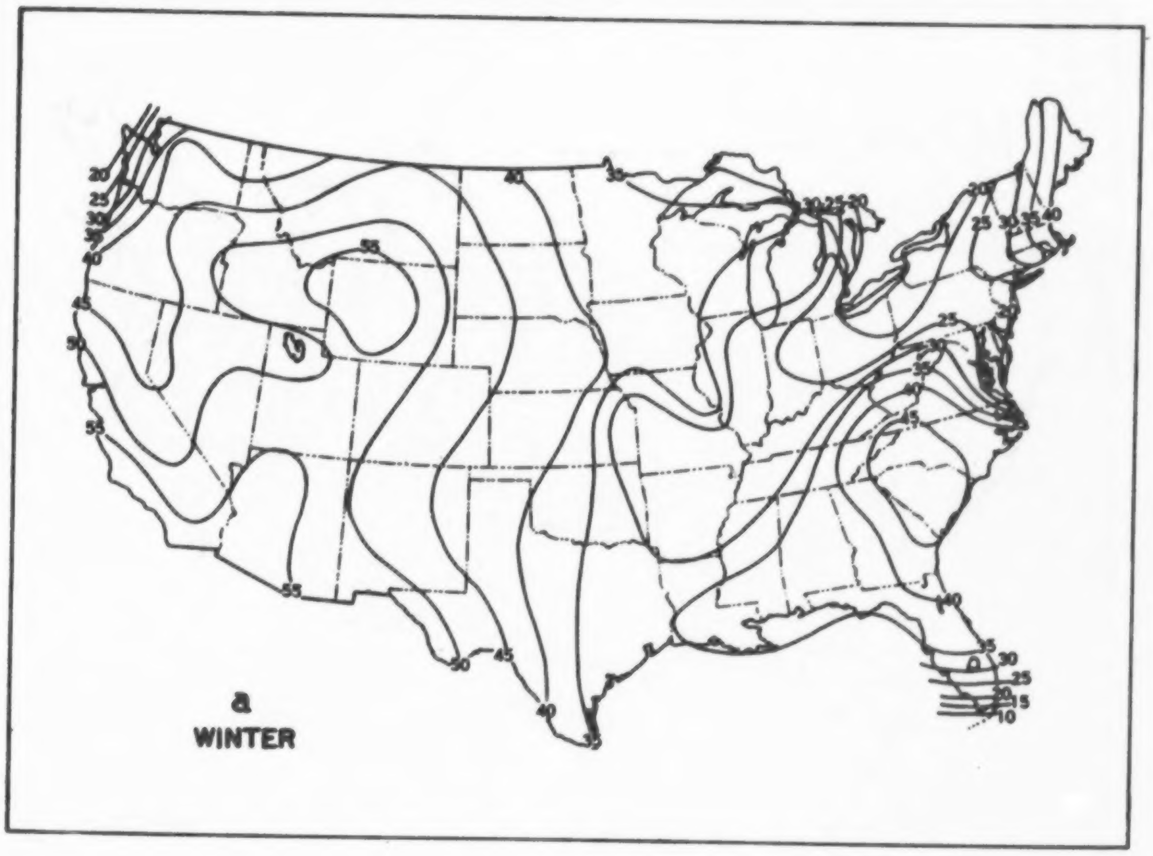
20
10
e
ANNUAL

FIGURE D-1 Concluded


a
WINTER
20
25
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35
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45
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55
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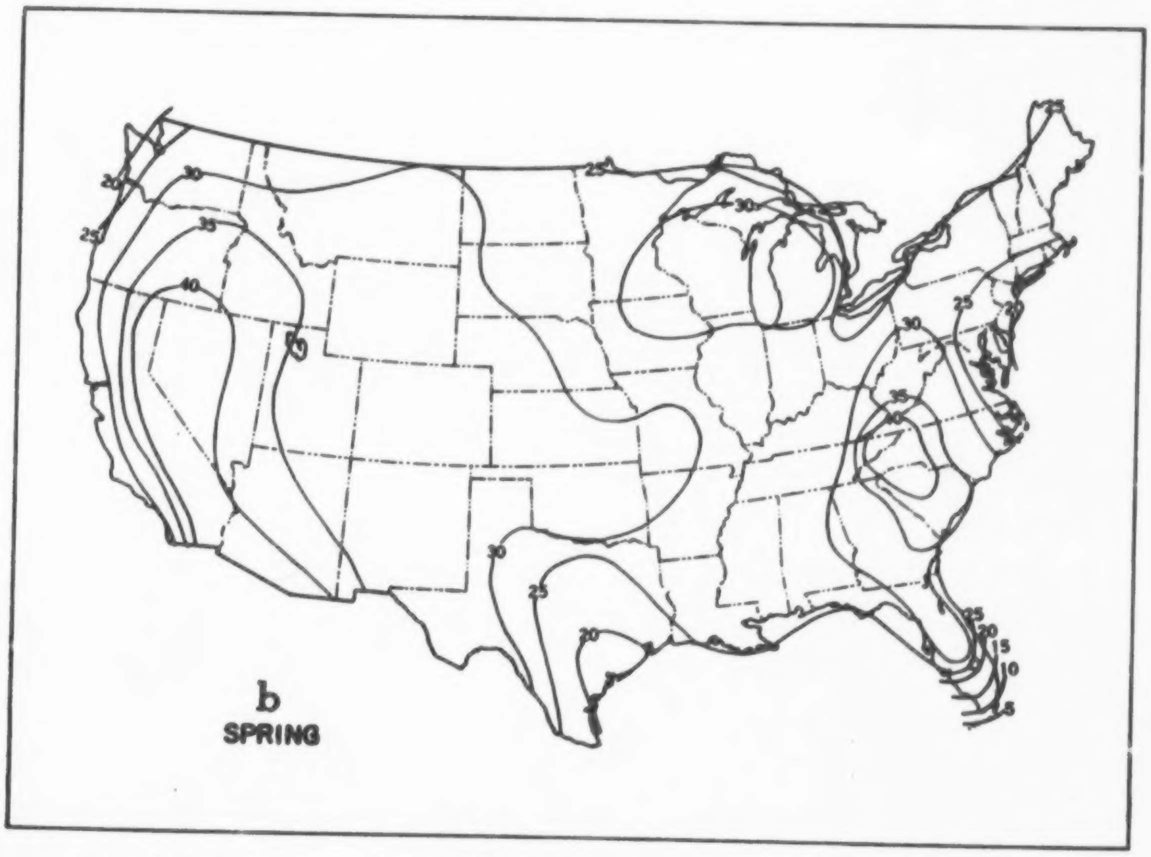
15


b
SPRING
20
25
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35
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15
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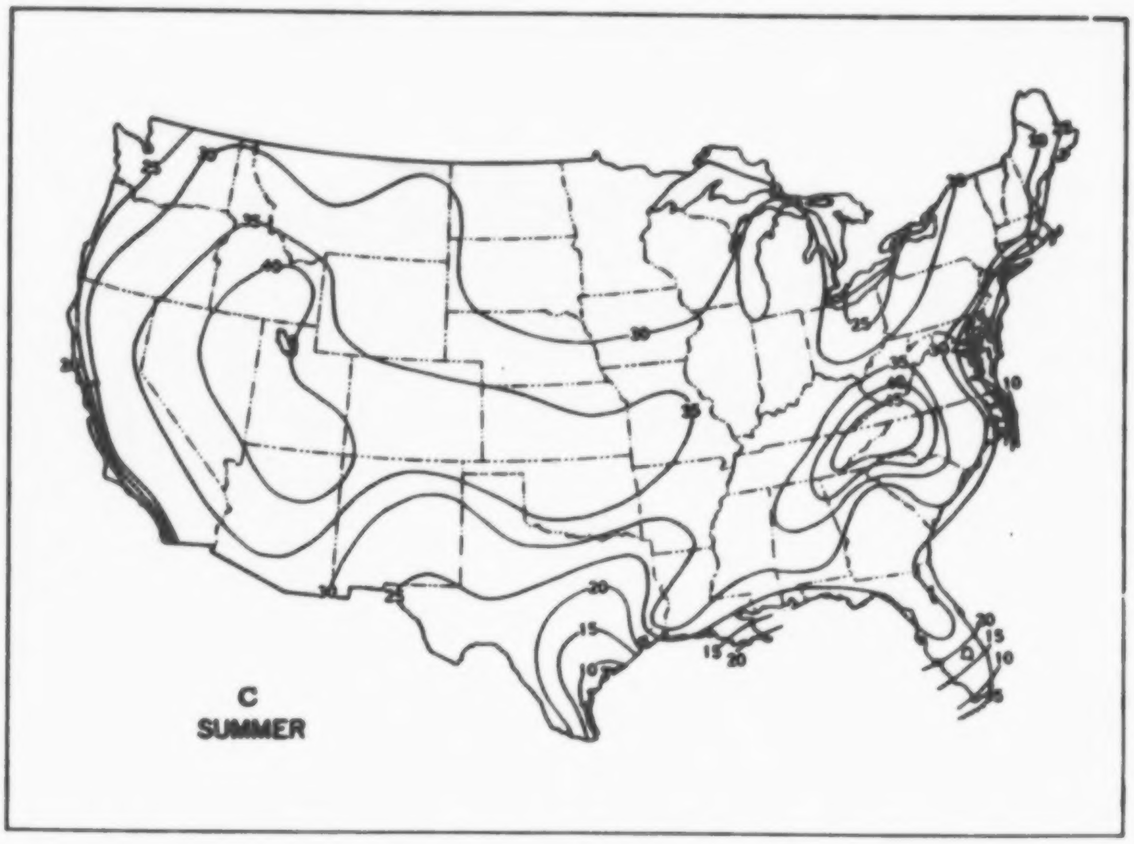
5

FIGURE D-2 INVERSION FREQUENCY (percent of total hours)

SOURCE: Hosler, C. R., Mon. Weather Rev. 89, 319-339 (1961).


c
SUMMER
25
30
35
40
30
25
30
25
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15
10
15
20
25
30
35
40
10
20
15
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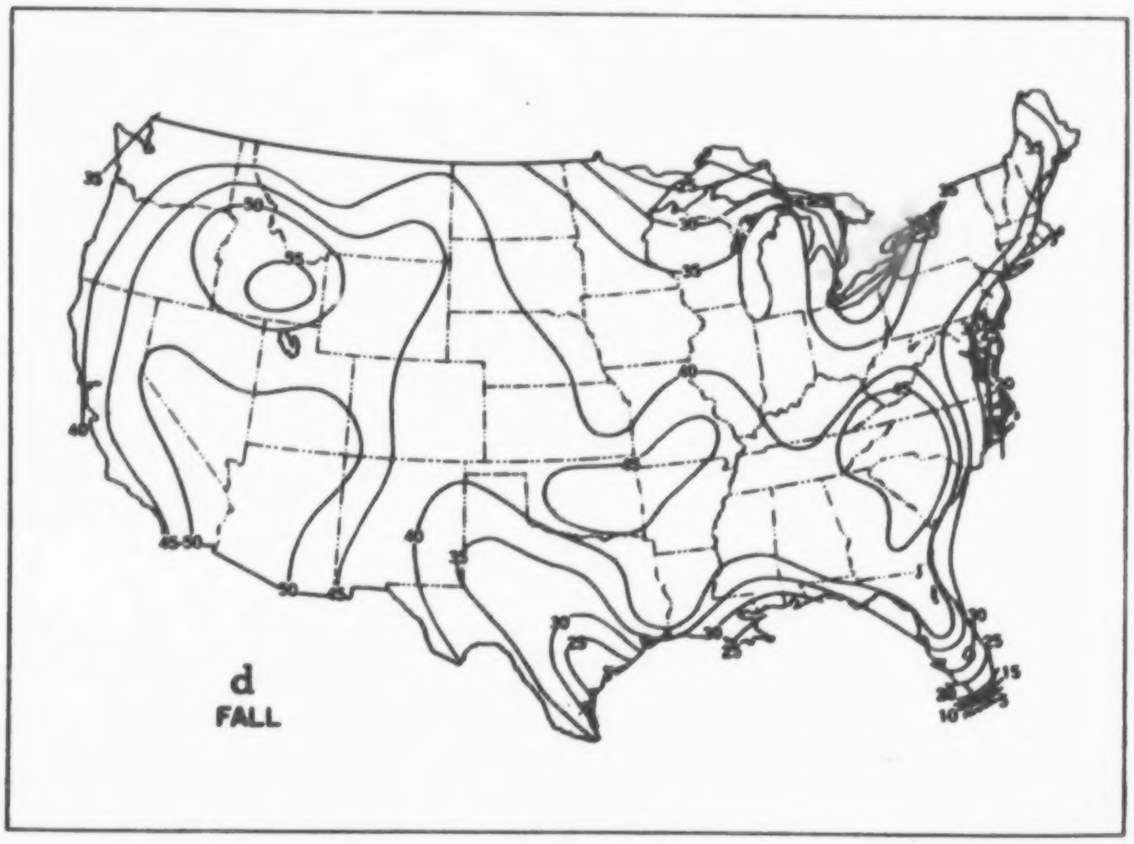
5


d
FALL
35
30
35
40
45-50
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40
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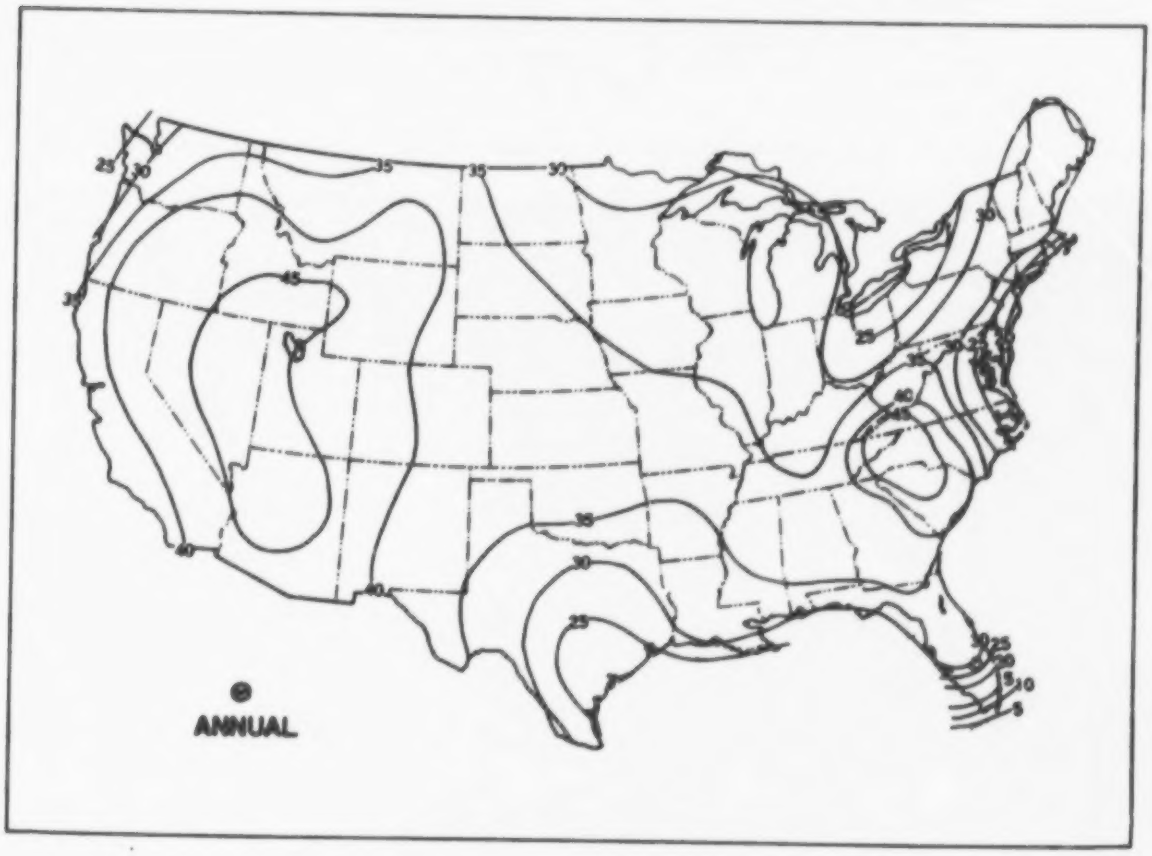
15
10
5

FIGURE D-2 Continued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10
5
ANNUAL

FIGURE D-2 Concluded

vigorous vertical air mixing occurs, usually because of thermal convection. From the standpoint of air pollution analysis, the mixing depth indicates the effective volume of air that is available to disperse and dilute stack effluents. Development of a surface turbulence layer is primarily a daytime phenomenon because the driving force is heating of the ground surface. The low-level inversion frequencies described above are primarily indications of nighttime periods of reduced potential for vertical mixing. Thus, by considering the average mixing depth and the inversion frequency together, it is possible to make a more comprehensive estimate of the potential hazards of air pollutant accumulations in a given area.

Estimates of mean MMD in the U.S. have been made by Holzworth,[1] who derived his patterns from data on average monthly temperature-height profiles and monthly averages of daily maximum temperatures. He was able to estimate the depth of the afternoon turbulence layer from the latter two variables by making reasonable assumptions about the conditions and influence of other meteorological variables. The resultant data represent monthly mean MMD because of the use of monthly averages of the daily maximum temperatures and the temperature profiles.

It is emphasized that at any given station during any specific time interval, the range of variation of the MMD about the reported average values can be quite large.

Figures D-3 to D-14 show the 12 monthly patterns of MMD over the United States. The isopleths of equal MMD are in units of 100 meters above the ground surface. As shown by Figs. D-3, D-4, D-11, D-12, and D-13, average MMDs are less than 1500 m over almost all of the U.S. The main exception is Southern Florida where convective activity provides practically an unlimited mixing depth. During midwinter -- December-January -- MMDs seldom exceed 800 m and are less than 500 m at many stations. Along the Mid-Atlantic and New England coasts the MMD is relatively shallow during most of the year, but especially so during the warmer months of the year. This is due, at least in part, to the effects of the cool Labrador current flowing along this coastal area.

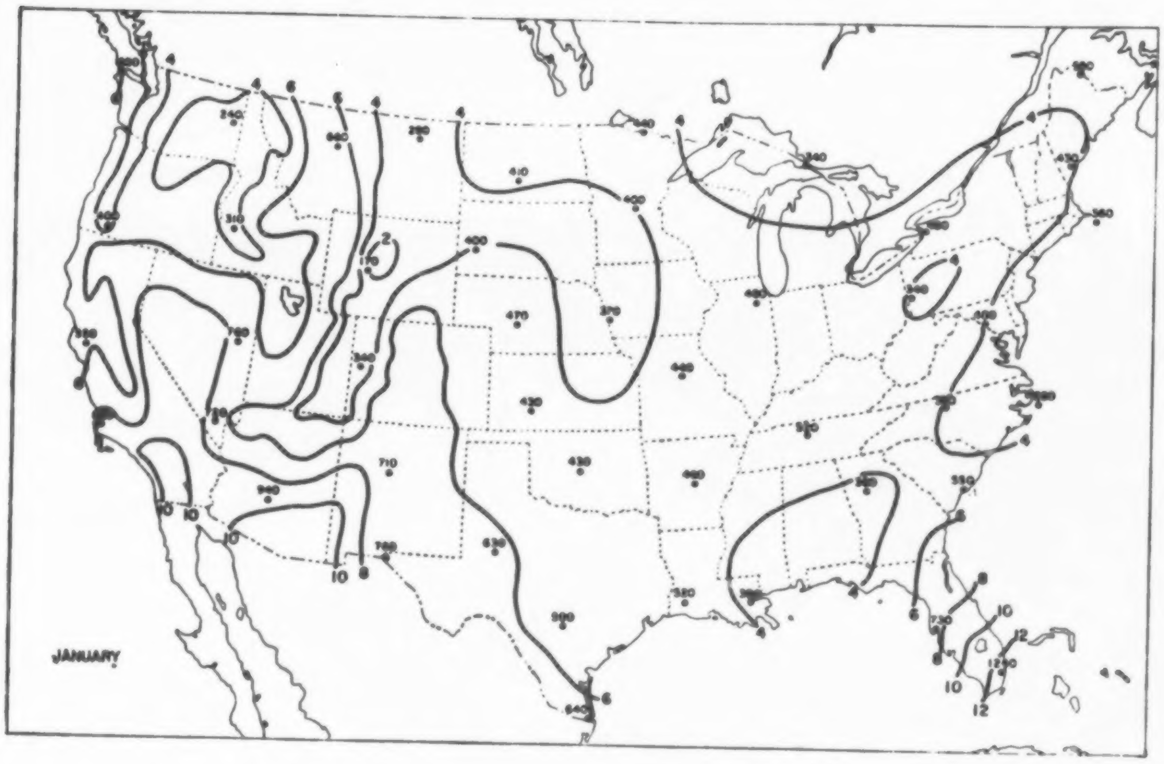


FIGURE D-3 MEAN MAXIMUM MIXING DEPTHS IN METERS ABOVE THE SURFACE DURING JANUARY. Isopleths are labeled in hundreds of meters.

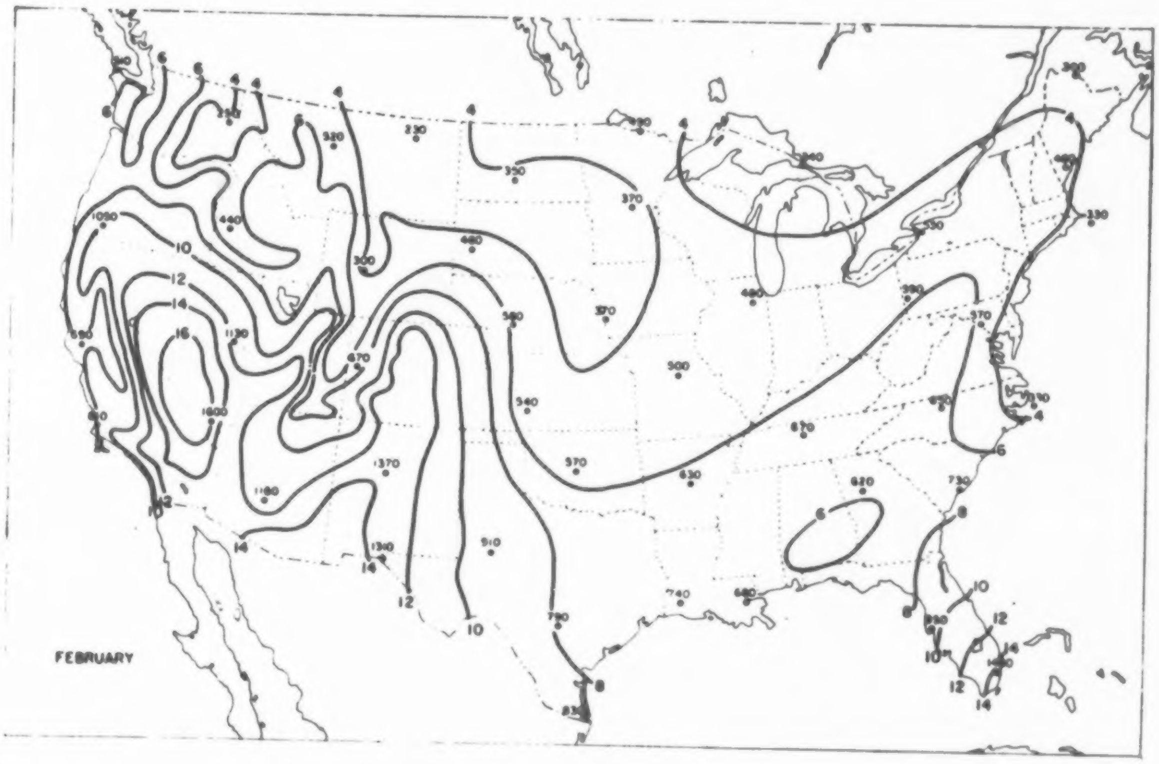


FIGURE D-4 MEAN MAXIMUM MIXING DEPTHS, FEBRUARY

SOURCE: Holzworth, G. C., Mon. Weather Rev. 92, 235-242 (1964).

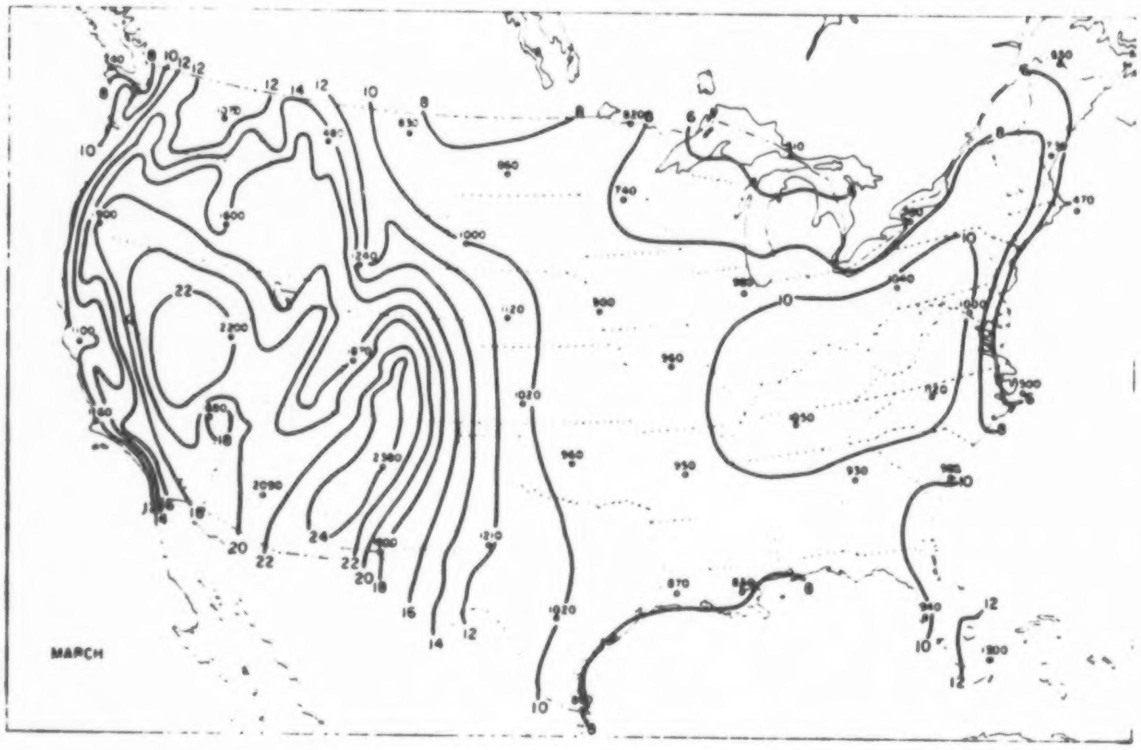


FIGURE D-5 MEAN MAXIMUM MIXING DEPTHS, MARCH

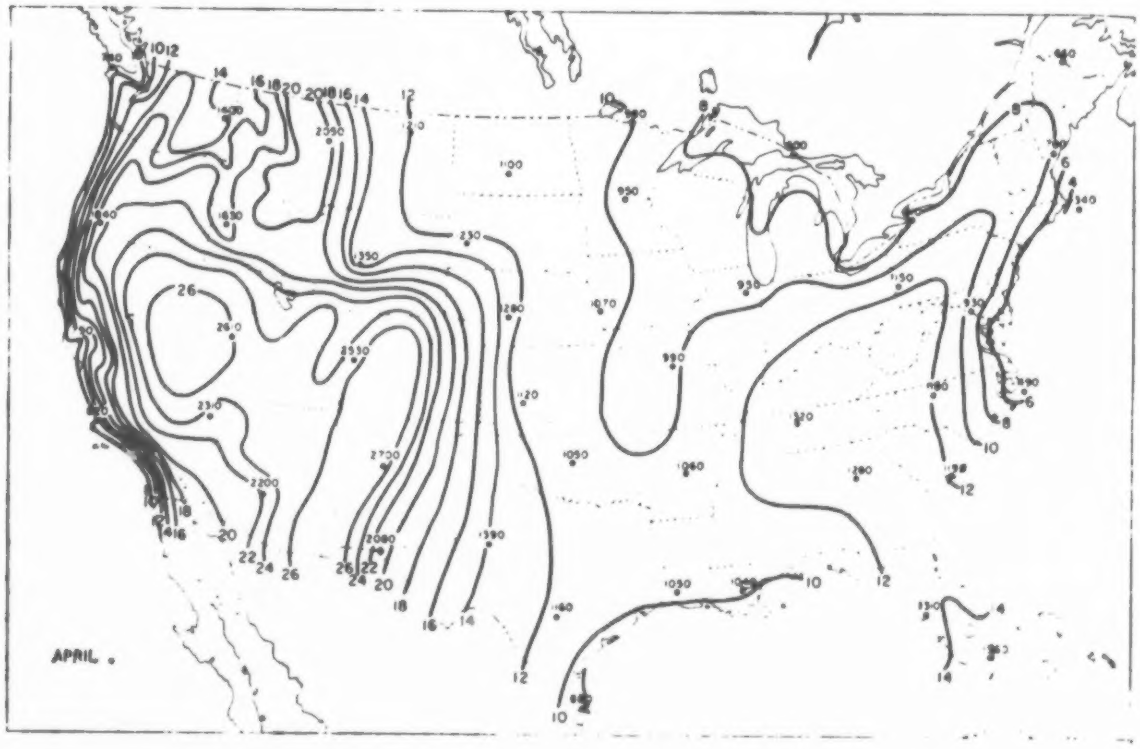


FIGURE D-6 MEAN MAXIMUM MIXING DEPTHS, APRIL

SOURCE: Holzworth, G. C., Mon. Weather Rev. 92, 235-242 (1964).

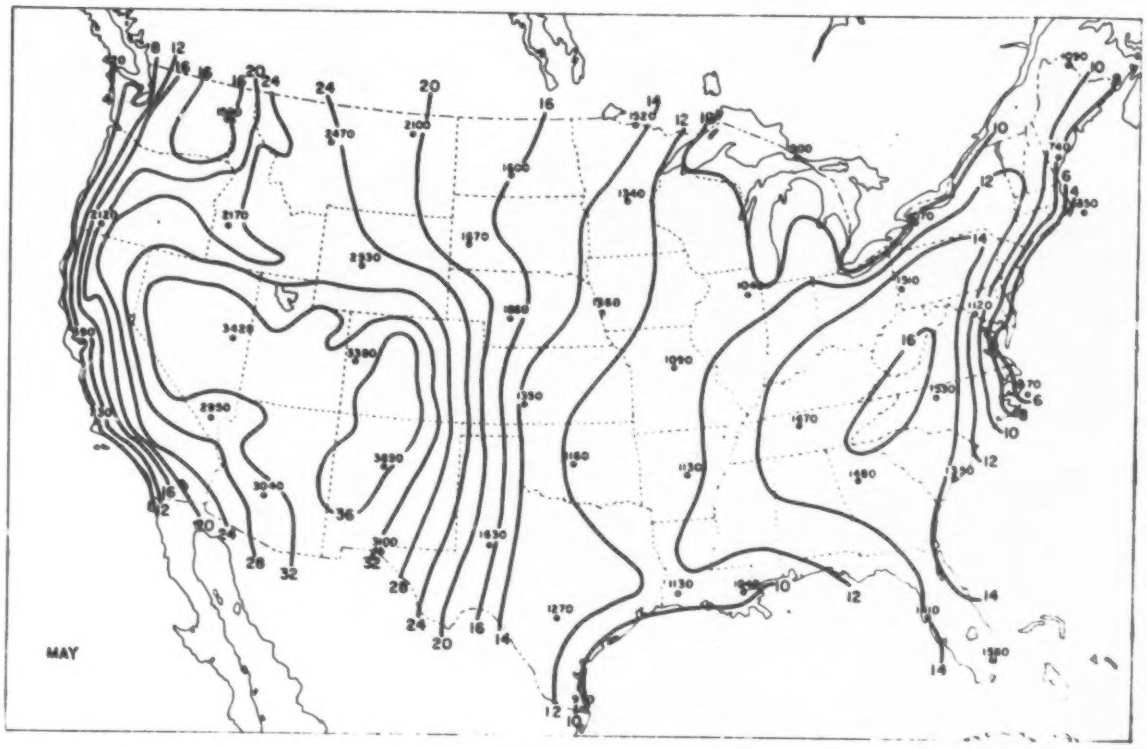


FIGURE D-7 MEAN MAXIMUM MIXING DEPTHS, MAY. Notice that over the western portion of the United States isopleths are in 400-m. intervals instead of the usual 200-m. intervals.

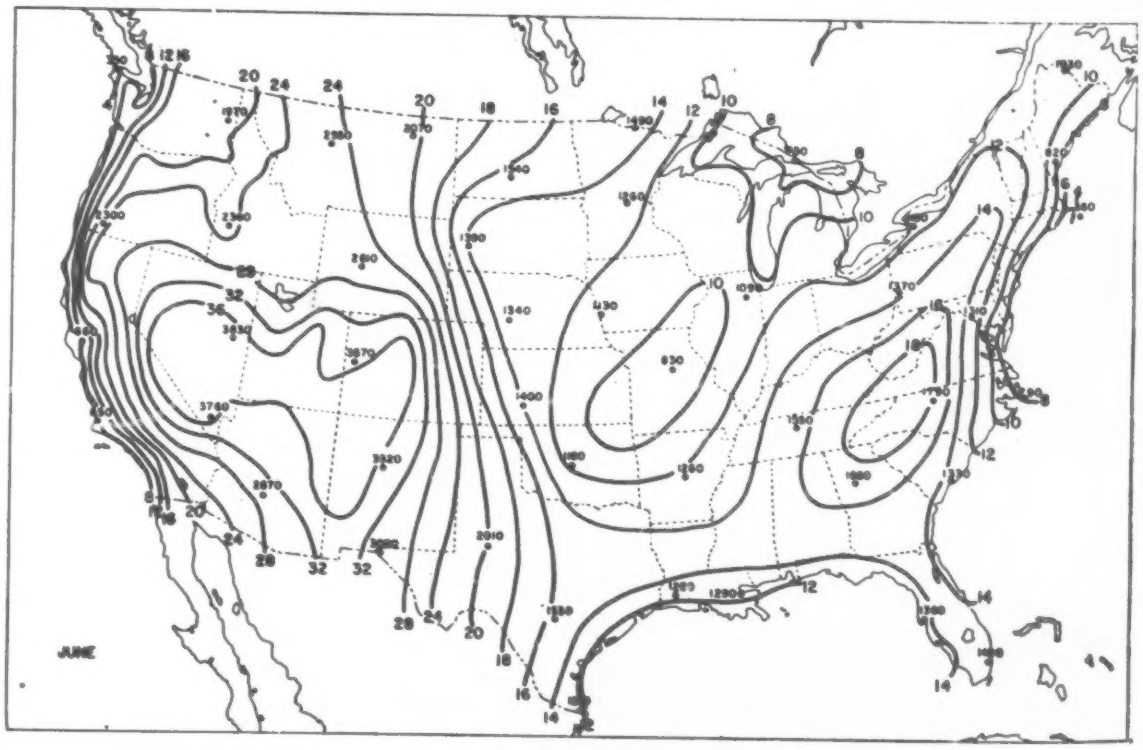


FIGURE D-8 MEAN MAXIMUM MIXING DEPTHS, JUNE

SOURCE: Holzworth, G. C., Mon. Weather Rev. 92, 235-242 (1964).

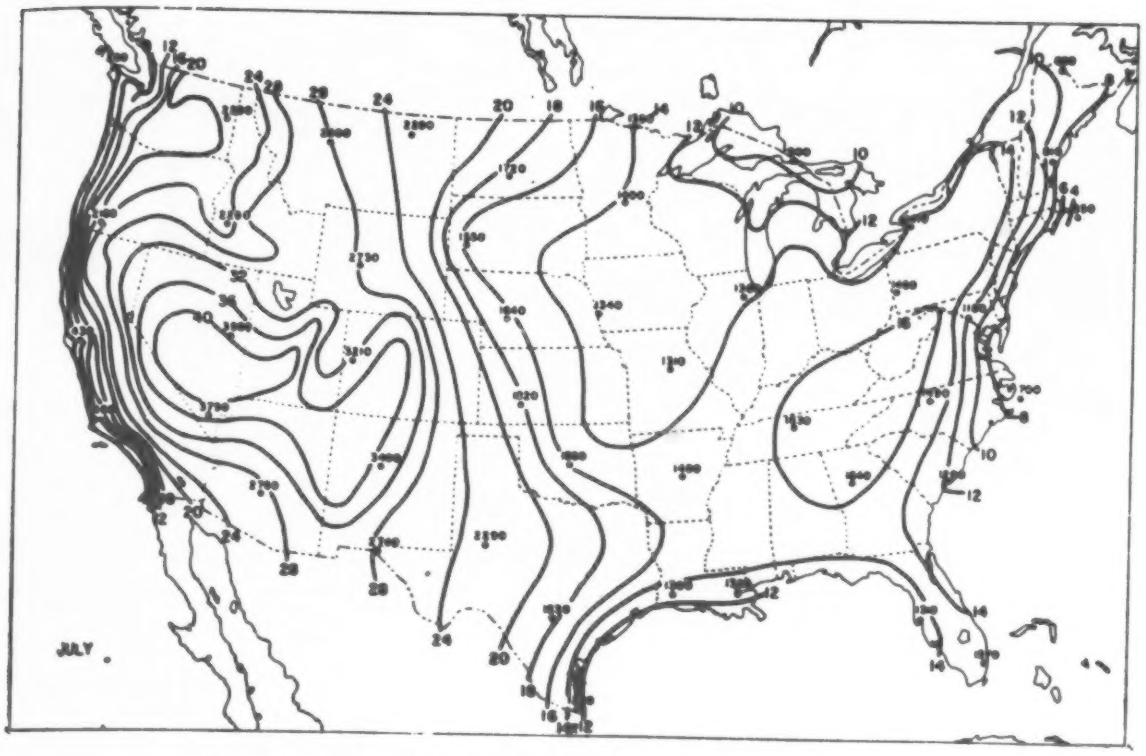


FIGURE D-9 MEAN MAXIMUM MIXING DEPTHS, JULY

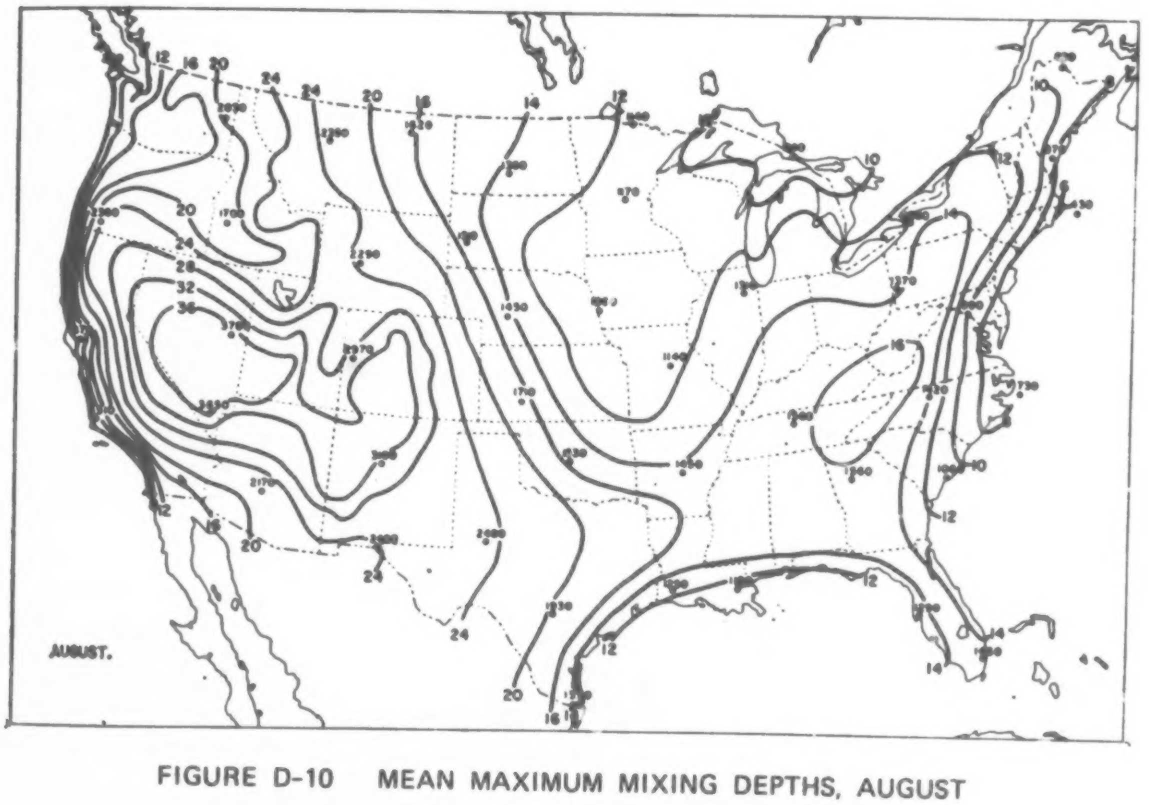


FIGURE D-10 MEAN MAXIMUM MIXING DEPTHS, AUGUST

SOURCE: Holzworth, G. C., Mon. Weather Rev. 92, 235-242 (1964).

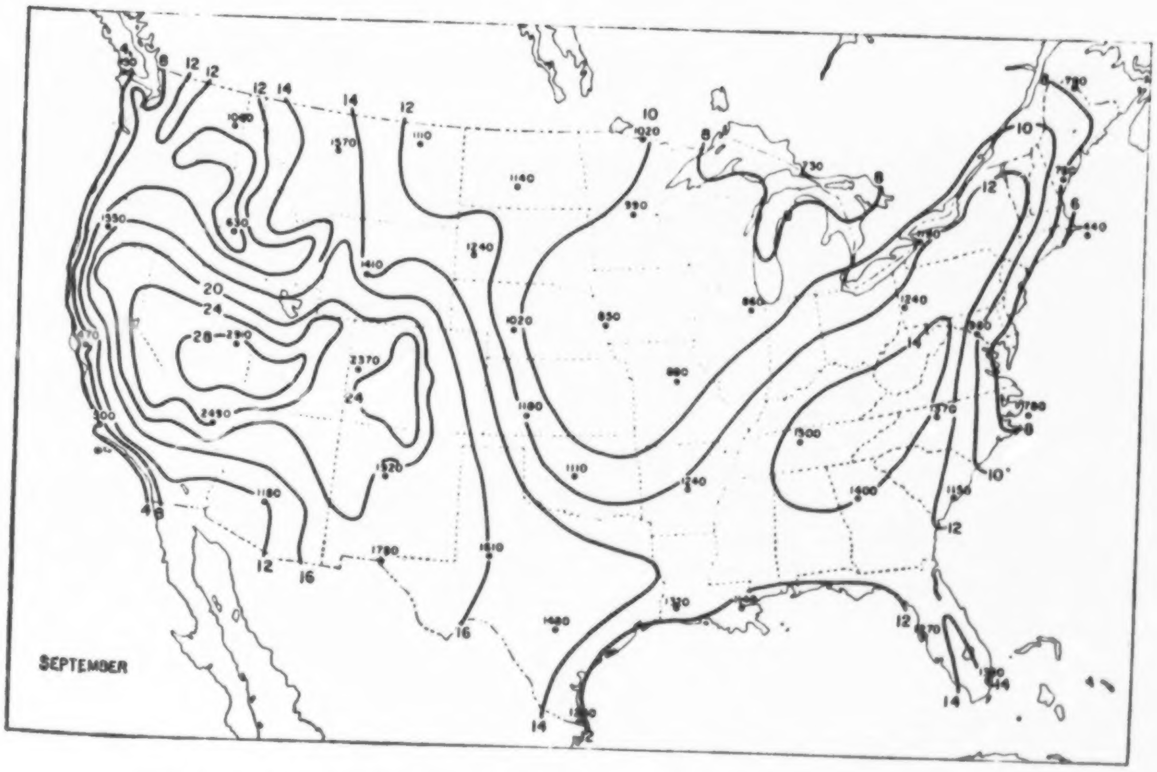


FIGURE D-11 MEAN MAXIMUM MIXING DEPTHS, SEPTEMBER

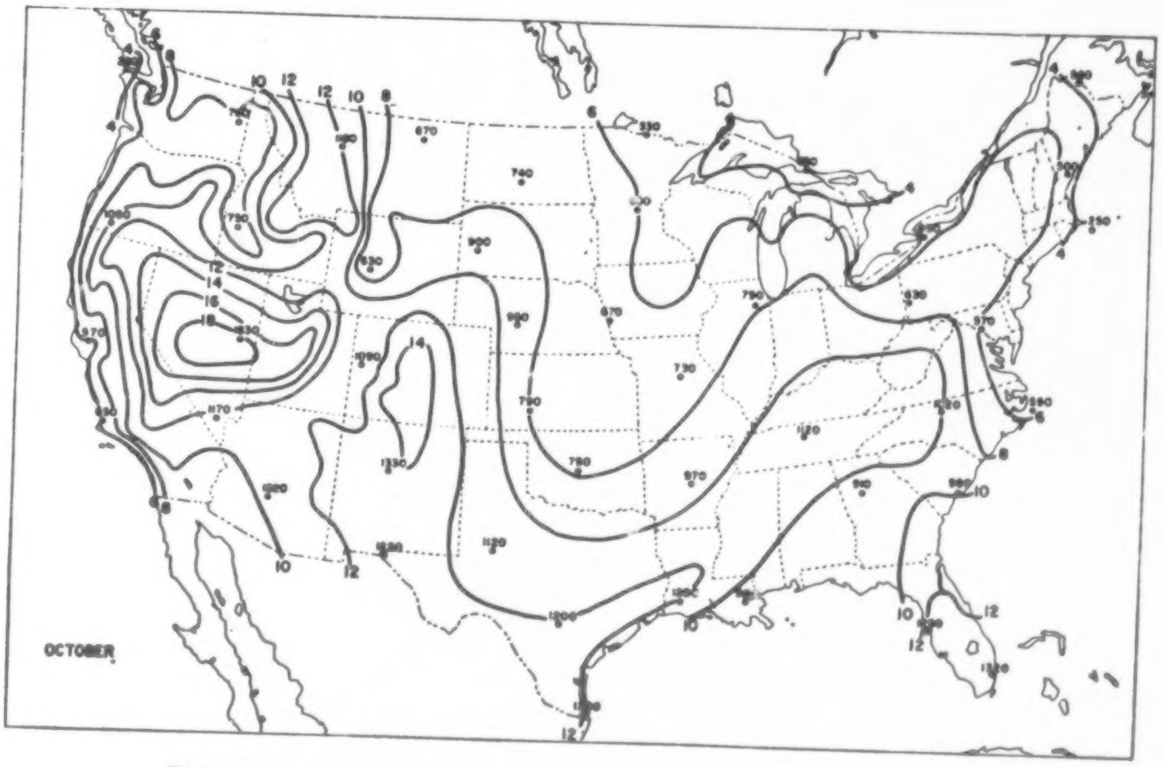


FIGURE D-12 MEAN MAXIMUM MIXING DEPTHS, OCTOBER

SOURCE: Holzworth, G. C., Mon. Weather Rev. 92, 235-242 (1964).

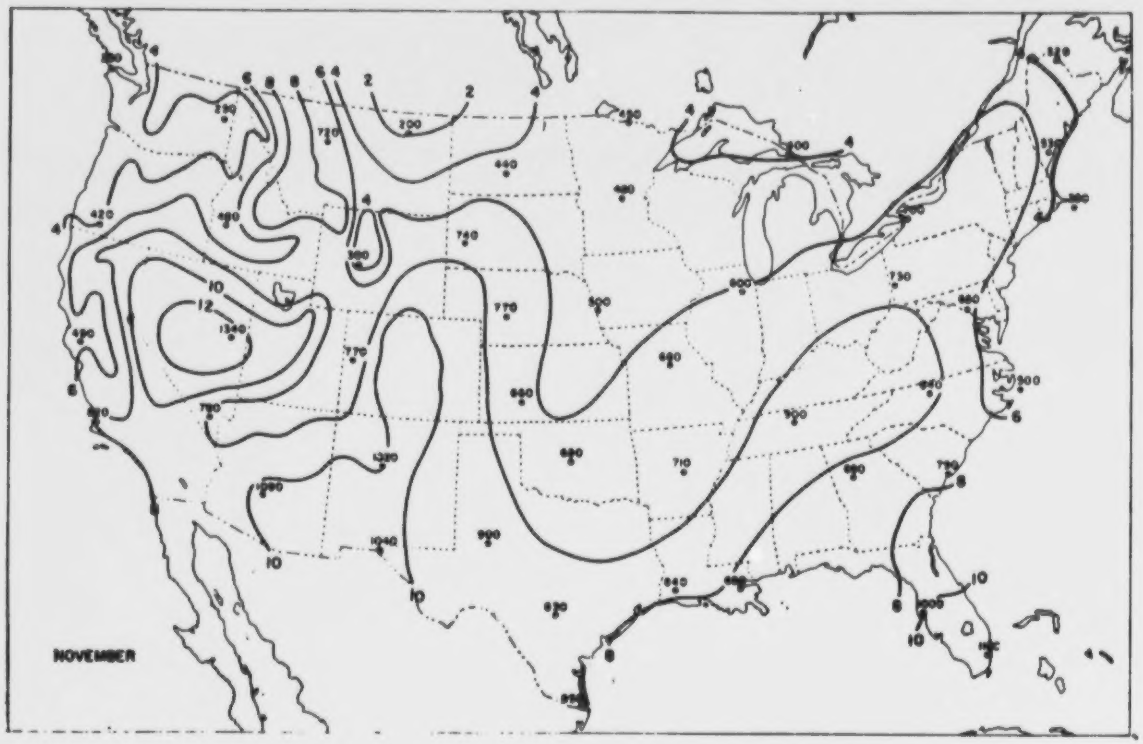


FIGURE D-13 MEAN MAXIMUM MIXING DEPTHS, NOVEMBER

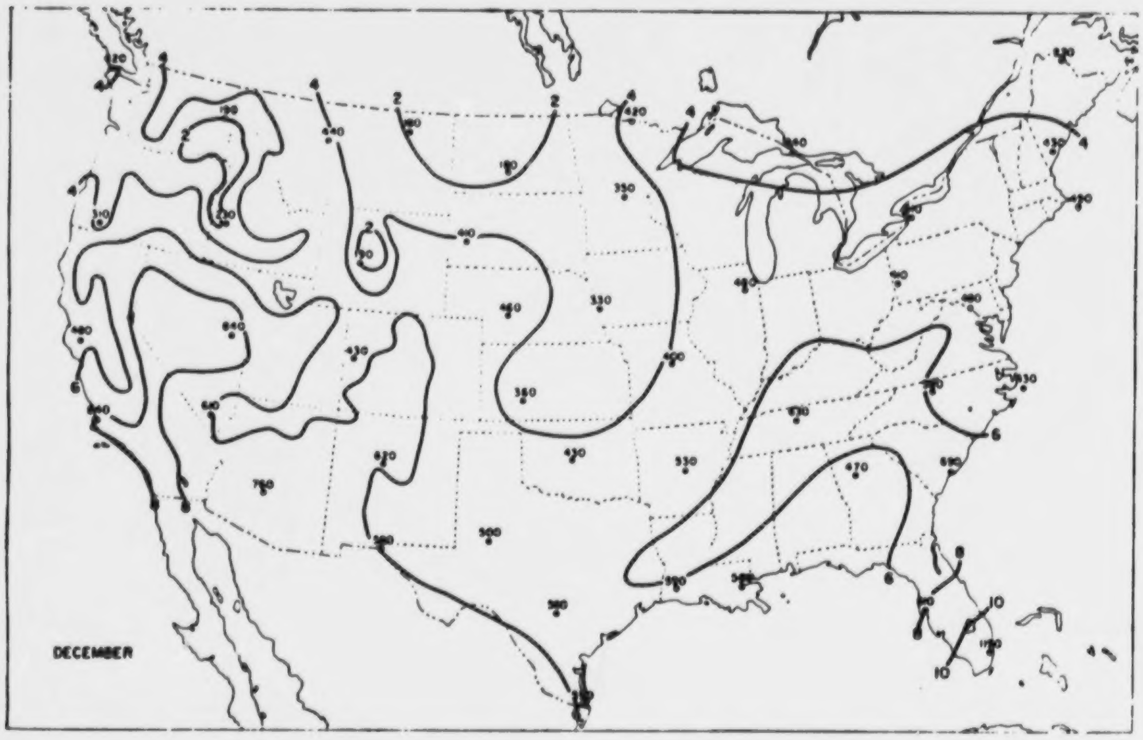


FIGURE D-14 MEAN MAXIMUM MIXING DEPTHS, DECEMBER

SOURCE: Holzworth, G. C., Mon. Weather Rev. 92, 235-242 (1964).

During the spring and summer months the MMD is practically unlimited over the Rockies and the Intermountain Plateau. This is a result of the high daytime temperatures characteristic of this area. It is interesting and important for the present purposes to consider this deep average afternoon mixing layer along with the high frequency of low-level nighttime inversions indicated in Hosler's data and shown by Figs. D-1C to D-1D and D-2C to D-2D. These show one facet of the dry desert area climate, namely, the large diurnal temperature range resulting from rapid daytime heating and equally rapid nighttime cooling. This cycle results in the formation of a stable radiation inversion at night and a deep, thermally mixed layer in the daytime. This phenomenon is of particular importance to the air pollution potentials of the numerous smelters in this desert region.

The Pacific coast is another area of relatively low summertime MMD, 500 m and less, which is the result of cold water offshore and a strong atmospheric subsidence along the coast. This low average MMD in the area is a major contributing factor to the serious air pollution situations found in California.

By considering together the data of Holzworth and Hosler relative to MMD and inversion frequency, certain conclusions about general climatic factors can be postulated. For example, Hosler[2] showed that stable layers, which usually began at the surface and were identified with nighttime periods, could be expected to occur on more than 50 percent of the nights over most of the U.S., on more than 70 percent of the nights over large areas, and on 80 to 90 percent of the nights over a number of areas in which numerous smelters are located. Consequently, it is a reasonable assumption[1] that at night the average depth of vertical mixing is less than 1000 feet over the areas -- including almost all of the U.S. -- where inversions occur on more than 50 percent of the nights. In areas where Hosler's data show inversions occurring on 80 percent or more of the nights, the average nighttime vertical mixing depth is probably less than 500 feet.[1] Thus, the nighttime vertical mixing over the U.S. is in general limited, and overnight pollutant accumulations are part of a typical climatic pattern.

Wind Direction Statistics

It is obvious that stack effluents will be carried by the local winds and that the frequency with which any given receptor may be exposed to an effluent will be determined by the frequency with which the wind blows from the source to the receptor. Such wind statistics can be determined only from instruments located in the specific source and receptor areas because of the numerous factors that affect local winds. Some of the more obvious of these are local topographic features such as mountains, valleys, lakes, and other major bodies of water.

Although obtaining specific exposure statistics would require local instrumentation, some useful general information can be obtained from maps showing surface wind statistics for a number of locations. Two such maps, one for January and one for July, are shown in Figs. D-15 and D-16, which present 10-year average wind roses as recorded by the Weather Bureau at the indicated locations. The wind roses indicate the percentages of time that the wind blew from the indicated directions and that there was calm. The patterns of most frequent wind directions, constituting a set of representative winds, can be used in consideration of wind effects over an area.

Wind statistics can also be treated as vectors, and be used to calculate a resultant wind vector. Such resultant vectors can be used to visualize the average, or resultant, flow patterns over an area. Vector resultant winds, giving both magnitudes and directions, at selected stations in the continental U.S. for January and July are shown in Figs. D-17 and D-18. As an example, the influx during winter of northern air masses into the Midwest and their subsequent eastward movement are easily seen. During the summer the dominant flow into the midwest is northward from the Gulf of Mexico.

Air Pollution Potential of Smelter Regions

The following discussion of the air pollution potentials of the five

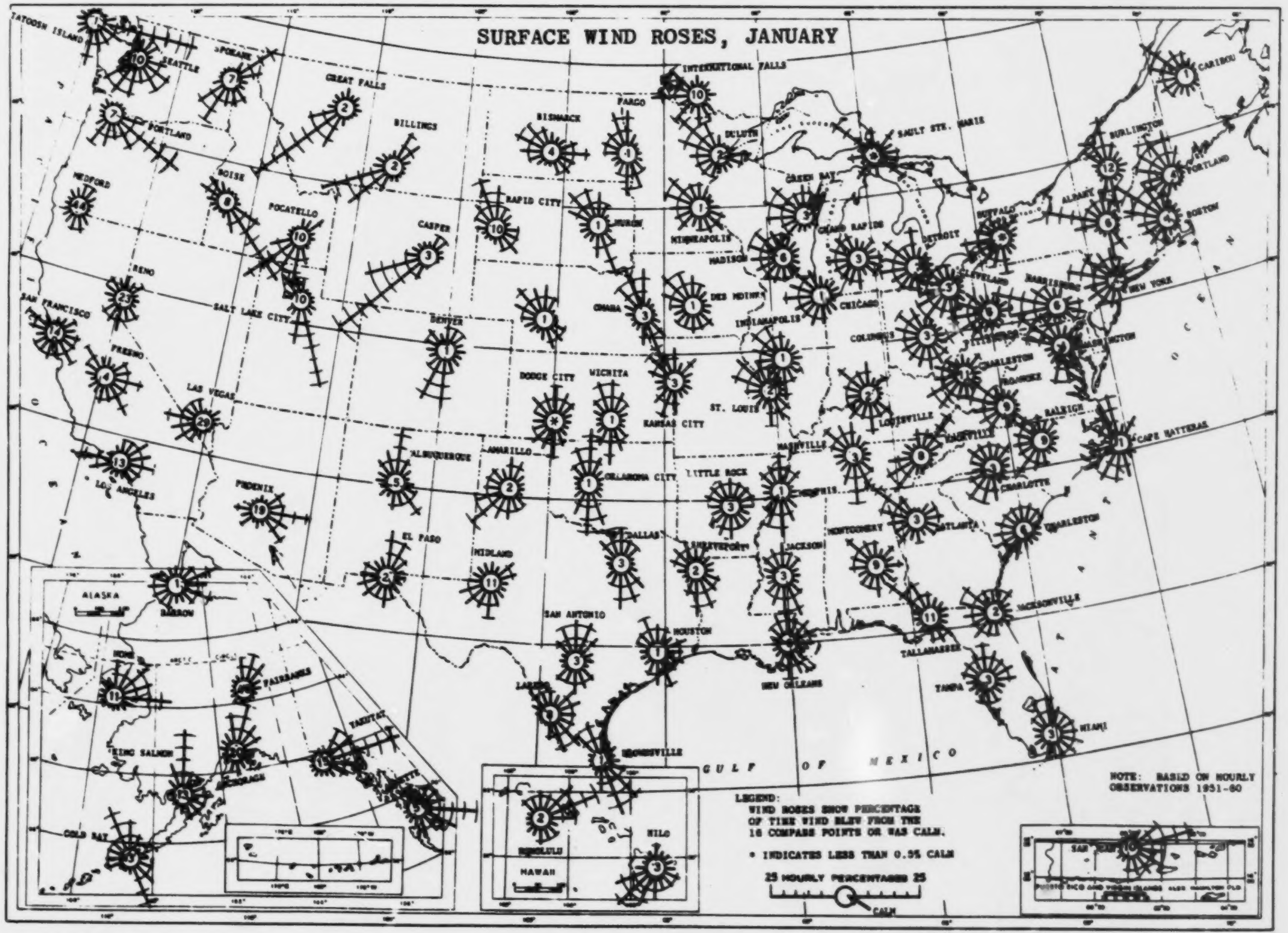
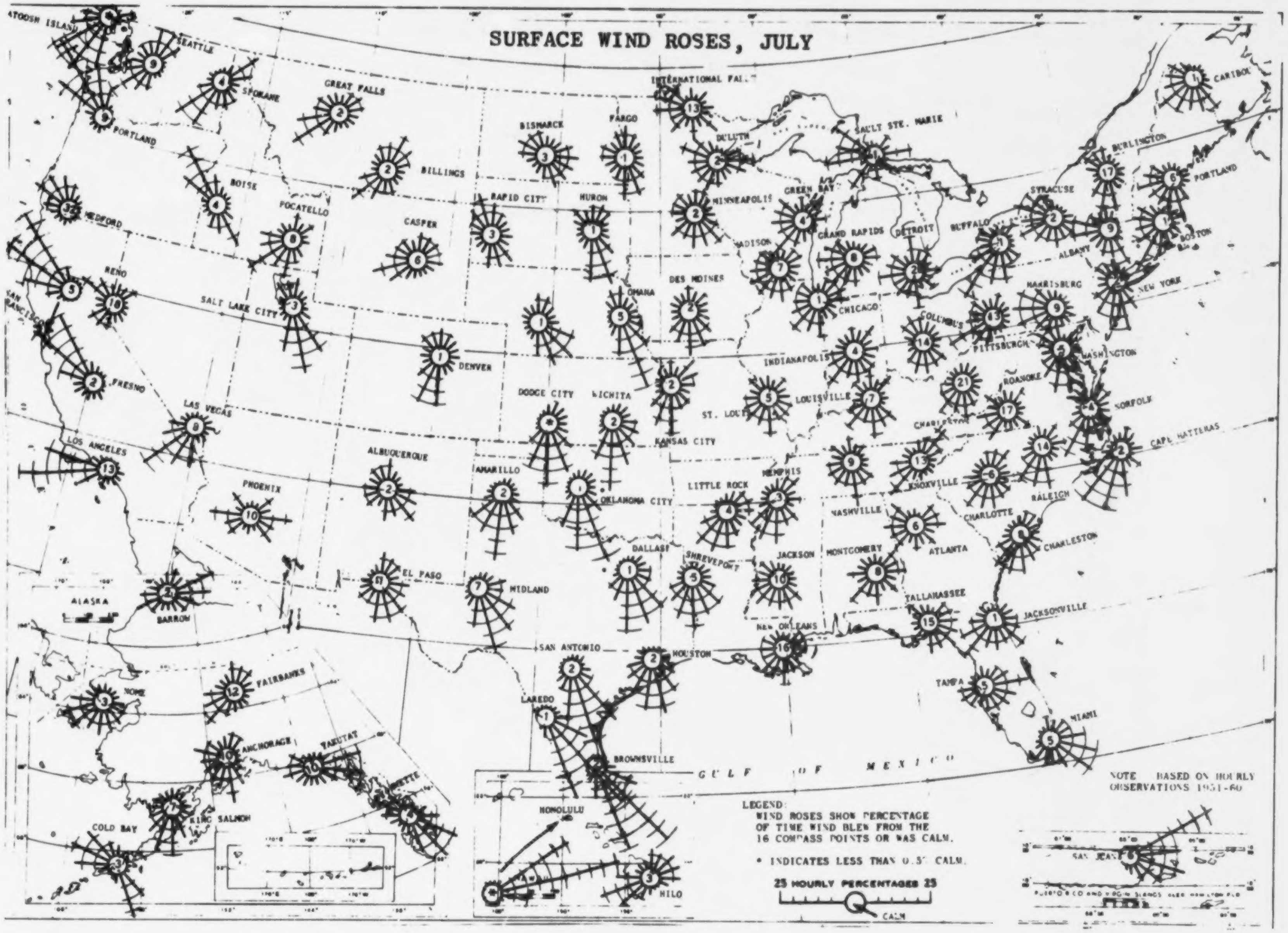

SURFACE WIND ROSES, JANUARY
TATOOSH ISLAND
SEATTLE
SPOKANE
GREAT FALLS
BILLINGS
PORTLAND
MEDFORD
BOISE
POCATELLO
CASPER
RENO
SAN FRANCISCO
SALT LAKE CITY
FRESNO
LAS VEGAS
LOS ANGELES
PHOENIX
DENVER
ALBUQUERQUE
AMARILLO
EL PASO
MIDLAND
BISMARCK
FARGO
INTERNATIONAL FALLS
RAPID CITY
HURON
DULUTH
MINNEAPOLIS
OMAHA
DES MOINES
DODGE CITY
WICHITA
KANSAS CITY
OKLAHOMA CITY
DALLAS
SAN ANTONIO
HOUSTON
LAREDO
BROWNSVILLE
SHREVEPORT
LITTLE ROCK
ST. LOUIS
MEMPHIS
JACKSON
NEW ORLEANS
SAULT STE. MARIE
GREEN BAY
MADISON
GRAND RAPIDS
CHICAGO
DETROIT
INDIANAPOLIS
COLUMBUS
CLEVELAND
BUFFALO
PITTSBURGH
LOUISVILLE
NASHVILLE
CHARLESTON
ROANOKE
MONTGOMERY
ATLANTA
CHARLOTTE
RALEIGH
CAPE HATTERAS
WASHINGTON
HARRISBURG
NEW YORK
ALBANY
BURLINGTON
PORTLAND
BOSTON
CARIBOU
CHARLESTON
JACKSONVILLE
TALLAHASSEE
TAMPA
MIAMI
GULF OF MEXICO
ALASKA
BARROW
NOME
FAIRBANKS
KING SALMON
ANCHORAGE
YAKUTAT
COLD BAY
HAWAII
HONOLULU
HILO
SAN JUAN
PUERTO RICO AND VIRGIN ISLANDS
LEGEND:
WIND ROSES SHOW PERCENTAGE
OF TIME WIND BLEW FROM THE
16 COMPASS POINTS OR WAS CALM.
• INDICATES LESS THAN 0.5% CALM
25 HOURLY PERCENTAGES 25
CALM
NOTE: BASED ON HOURLY
OBSERVATIONS 1951-60

FIGURE D-15 SURFACE WIND ROSES, JANUARY

SOURCE: Selected Climatic Maps of the United States, Environmental Science Services Administration (1966).


SURFACE WIND ROSES, JULY
TATOOSH ISLAND
SEATTLE
PORTLAND
SPOKANE
GREAT FALLS
BILLINGS
BOISE
POCATELLO
CASPER
MEDFORD
RENO
SALT LAKE CITY
SAN FRANCISCO
FRESNO
LAS VEGAS
LOS ANGELES
PHOENIX
DENVER
ALBUQUERQUE
EL PASO
BISMARCK
FARGO
RAPID CITY
HURON
OMAHA
DES MOINES
DODGE CITY
WICHITA
KANSAS CITY
AMARILLO
OKLAHOMA CITY
MIDLAND
DALLAS
SHREVEPORT
SAN ANTONIO
HOUSTON
LAREDO
BROWNSVILLE
INTERNATIONAL FALLS
DULUTH
MINNEAPOLIS
GREEN BAY
SAULT STE. MARIE
MADISON
GRAND RAPIDS
DETROIT
CHICAGO
ST. LOUIS
INDIANAPOLIS
LOUISVILLE
LITTLE ROCK
MEMPHIS
NASHVILLE
JACKSON
NEW ORLEANS
MONTGOMERY
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TALLAHASSEE
BUFFALO
COLUMBUS
PITTSBURGH
CHARLESTON
KNOXVILLE
ROANOKE
CHARLOTTE
RALEIGH
CHARLESTON
JACKSONVILLE
TAMPA
MIAMI
SYRACUSE
ALBANY
HARRISBURG
WASHINGTON
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CAPE HATTERAS
NEW YORK
BOSTON
PORTLAND
BURLINGTON
CARIBOU
GULF OF MEXICO
ALASKA
BARROW
NOME
FAIRBANKS
ANCHORAGE
YAKUTAT
KING SALMON
COLD BAY
HONOLULU
HILO
SAN JUAN
PUERTO RICO AND VIRGIN ISLANDS
LEGEND:
WIND ROSES SHOW PERCENTAGE OF TIME WIND BLEW FROM THE 16 COMPASS POINTS OR WAS CALM.
• INDICATES LESS THAN 0.5% CALM.
25 HOURLY PERCENTAGES 25
CALM
NOTE BASED ON HOURLY OBSERVATIONS 1951-60

FIGURE D-16 SURFACE WIND ROSES, JULY

SOURCE: Selected Climatic Maps of the United States, Environmental Science Services Administration (1966).

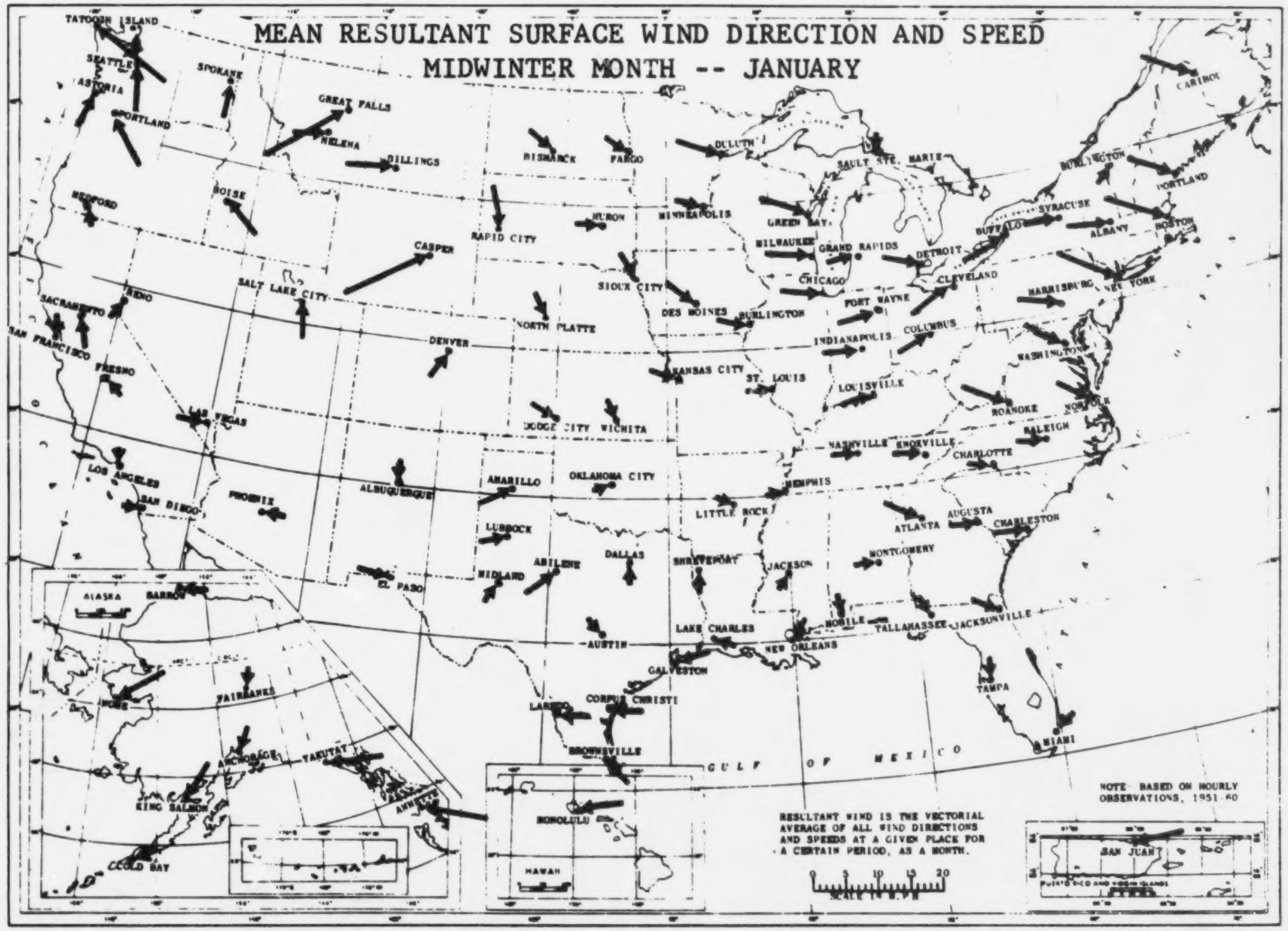
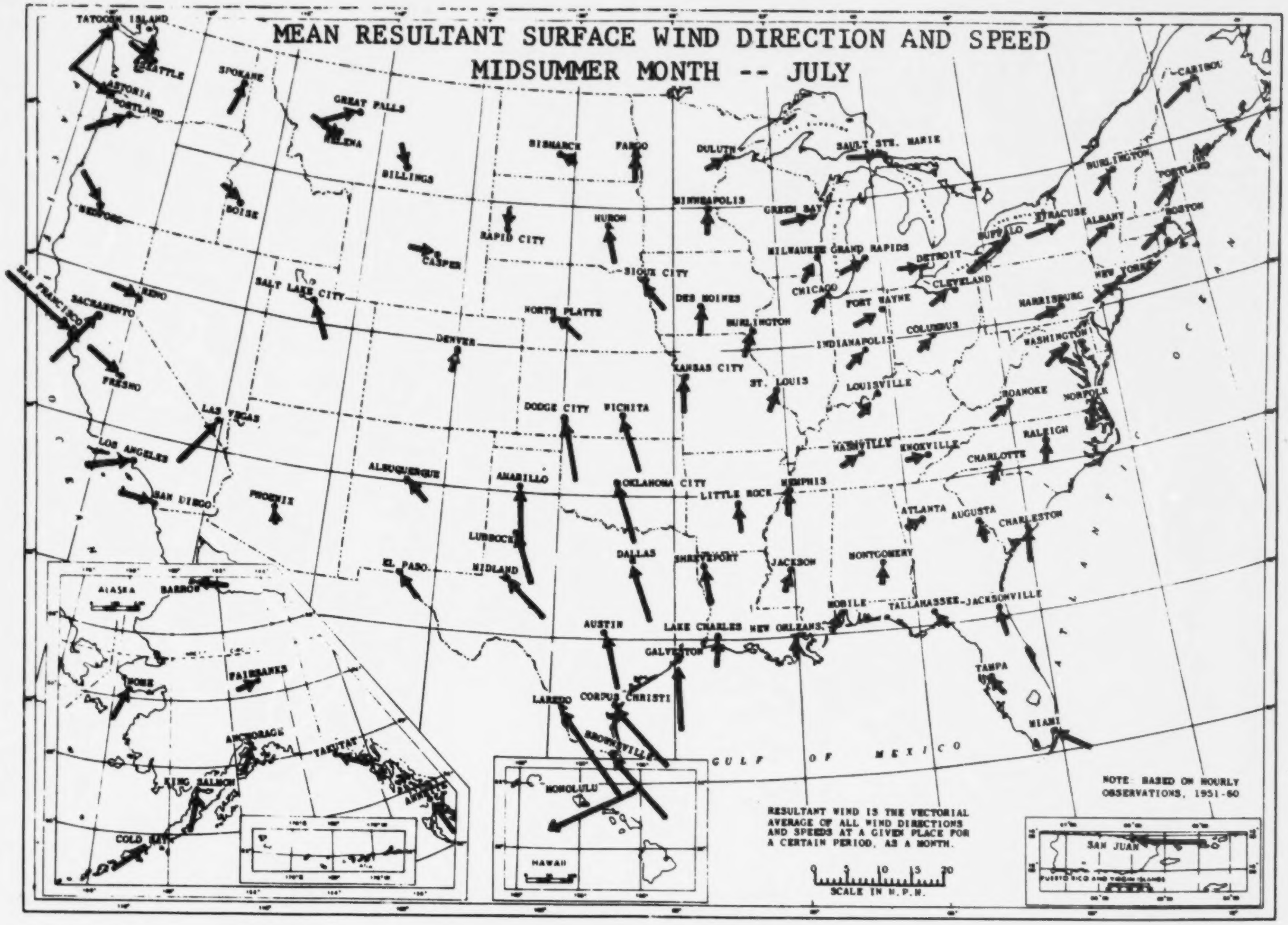

MEAN RESULTANT SURFACE WIND DIRECTION AND SPEED
MIDWINTER MONTH -- JANUARY
TATOOSH ISLAND
SEATTLE
ASTORIA
PORTLAND
SPOKANE
GREAT FALLS
HELENA
BILLINGS
BOISE
MEDFORD
CASPER
RAPID CITY
BISMARCK
FARGO
DULUTH
SAULT STE. MARIE
HURON
MINNEAPOLIS
GREEN BAY
MILWAUKEE
GRAND RAPIDS
DETROIT
BURLINGTON
PORTLAND
CARIBOU
BUFFALO
SYRACUSE
ALBANY
BOSTON
NEW YORK
HARRISBURG
CLEVELAND
CHICAGO
FORT WAYNE
SALT LAKE CITY
RENO
SACRAMENTO
SAN FRANCISCO
FRESNO
SIOUX CITY
DES MOINES
BURLINGTON
NORTH PLATTE
DENVER
INDIANAPOLIS
COLUMBUS
WASHINGTON
KANSAS CITY
ST. LOUIS
LOUISVILLE
ROANOKE
NORFOLK
LAS VEGAS
DODGE CITY
WICHITA
NASHVILLE
KNOXVILLE
RALEIGH
CHARLOTTE
LOS ANGELES
SAN DIEGO
PHOENIX
ALBUQUERQUE
AMARILLO
OKLAHOMA CITY
MEMPHIS
LITTLE ROCK
ATLANTA
AUGUSTA
CHARLESTON
LUBBOCK
MIDLAND
ABILENE
DALLAS
SHREVEPORT
JACKSON
MONTGOMERY
EL PASO
MOBILE
TALLAHASSEE
JACKSONVILLE
AUSTIN
LAKE CHARLES
NEW ORLEANS
GALVESTON
TAMPA
LAREDO
CORPUS CHRISTI
BROWNSVILLE
MIAMI
GULF OF MEXICO
ALASKA
BARROW
NOME
FAIRBANKS
ANCHORAGE
YAKUTAT
KING SALMON
ANNETTE
COLD BAY
HONOLULU
HAWAII
SAN JUAN
PUERTO RICO AND VIRGIN ISLANDS
RESULTANT WIND IS THE VECTORIAL AVERAGE OF ALL WIND DIRECTIONS AND SPEEDS AT A GIVEN PLACE FOR A CERTAIN PERIOD, AS A MONTH.
0 5 10 15 20
SCALE IN M.P.H
NOTE: BASED ON HOURLY OBSERVATIONS, 1951-60

FIGURE D-17 MEAN RESULTANT SURFACE WIND DIRECTION AND SPEED—JANUARY

SOURCE: Selected Climatic Maps of the United States, ESSA (1966).


MEAN RESULTANT SURFACE WIND DIRECTION AND SPEED
MIDSUMMER MONTH -- JULY
TATOOSH ISLAND
SEATTLE
ASTORIA
PORTLAND
SPOKANE
GREAT FALLS
HELENA
BILLINGS
BISMARCK
FARGO
DULUTH
SAULT STE. MARIE
CARIBOU
BURLINGTON
PORTLAND
MEDFORD
BOISE
RAPID CITY
HURON
MINNEAPOLIS
GREEN BAY
SYRACUSE
ALBANY
BOSTON
CASPER
SIOUX CITY
MILWAUKEE
GRAND RAPIDS
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DES MOINES
CHICAGO
FORT WAYNE
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COLUMBUS
WASHINGTON
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KANSAS CITY
ST. LOUIS
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ROANOKE
NORFOLK
LAS VEGAS
DODGE CITY
WICHITA
NASHVILLE
KNOXVILLE
RALEIGH
CHARLOTTE
LOS ANGELES
ALBUQUERQUE
AMARILLO
OKLAHOMA CITY
LITTLE ROCK
MEMPHIS
SAN DIEGO
PHOENIX
ATLANTA
AUGUSTA
CHARLESTON
LUBBOCK
DALLAS
SHREVEPORT
JACKSON
MONTGOMERY
EL PASO
MIDLAND
MOBILE
TALLAHASSEE
JACKSONVILLE
AUSTIN
LAKE CHARLES
NEW ORLEANS
GALVESTON
TAMPA
LAREDO
CORPUS CHRISTI
BROWNSVILLE
MIAMI
GULF OF MEXICO
ALASKA
BARROW
NOME
FAIRBANKS
ANCHORAGE
YAKUTAT
KING SALMON
COLD BAY
ANNETTE
HONOLULU
HAWAII
SAN JUAN
NOTE: BASED ON HOURLY OBSERVATIONS, 1951-60
RESULTANT WIND IS THE VECTORIAL AVERAGE OF ALL WIND DIRECTIONS AND SPEEDS AT A GIVEN PLACE FOR A CERTAIN PERIOD, AS A MONTH.
0 5 10 15 20
SCALE IN M.P.H.

FIGURE D-18 MEAN RESULTANT SURFACE WIND DIRECTION AND SPEED—JULY

SOURCE: Selected Climatic Maps of the United States, ESSA (1966) smelter regions previously defined is based on the general meteorological factors affecting the areas and does not consider whether air pollution problems have actually been experienced by smelters located there. However, publicly available information indicates that at some periods air pollution damage has in fact been attributed to smelter operations in each of the five regions considered.

1. Appalachian Area. This district is affected by a relatively satisfactory set of weather conditions as far as air pollution potential is concerned, even though it encompasses Donora, Pennsylvania, the scene of one of the most serious air pollution episodes in United States history. The main liabilities are presented by the combination of narrow valleys and nocturnal inversions that can serve to channel and stagnate effluents from local sources. Periodically this Appalachian region is severely affected by stagnating high pressure weather systems. These events can be major contributors to severe local air pollution incidents, such as the Donora episode, but under more typical conditions the prevalent nocturnal inversions shown by Figs. D-1 and D-2 are broken by the development of a moderate afternoon mixing layer, as shown by Figs. D-3 to D-14. In some areas the predominance of southerly winds could bias the exposure of a particular area to a given nearby source, and it can be expected that more severe cumulative air pollution effects might be found to the north of major sources.

2. Midwestern Area. This large area covers the smelter regions in the Texas Panhandle, Oklahoma, Kansas, Missouri, Illinois, and Michigan. These regions are considered together because the terrain is generally flat, resulting in wind directions that are governed by prevailing weather systems rather than topography. Compared with other areas of the nation, inversion frequencies are relatively low, as indicated by Figs. D-1 and D-2. Maximum mixing depths, Figs. D-3 to D-14, show some tendency for restricted vertical diffusion in the cooler months of the year, i.e., November through February, but for most months mixing depths are relatively high.

Wind conditions in this area are generally favorable for avoiding excessive accumulations of air pollutants. Wind speeds in most areas average in excess of 10 mph and the wind rose data, Figs. D-15 and D-16, indicate considerable variability. When inversions do occur in this area, an effluent layer can spread laterally because it is not channeled by the terrain. Hence, the accumulation of pollutants should tend to be less dense than in mountainous terrain, and the fumigation occurring during the inversion breakup will probably be less severe.

Apart from fumigations, the most serious smelter problems are likely to occur as a result of looping of plumes or of use of low stacks.

3. Southwestern Desert Area. This is a large area including the states of Arizona, Nevada, Utah, New Mexico, and the El Paso area of Texas. The major meteorological air pollution factor is the strong diurnal cycle normally present in the stability pattern. This cyclic factor is shown by a comparison of the MMD and the inversion frequency data. In the southwest, inversions in the lowest 500 ft are shown to be at a relative maximum for the nation (Figs. D-1 and D-2), while at the same time afternoon mean MMD are also greater than for any other area. This cyclic situation is a natural result of the area climate.

The strong diurnal cycle in stability is reflected in a similarly strong diurnal cycle in air pollution conditions. During the night the strong surface inversion produces conditions that are conducive to the accumulation of pollutants in a rather thin layer at some altitude above the ground. In this southwestern desert area, where the terrain is often irregular in the smelter areas, the accumulation of this nocturnal pollution layer will often be restricted to the valley containing the source. It is also to be expected that nighttime winds will be strongly influenced by the terrain. Thus the nocturnal effluent layer will characteristically be observed to drift or meander downslope or downvalley with the flow of the nighttime drainage wind.

The daytime phase of this diurnal cycle is characterized by rapidly developing and rather deep connective activity, which may have a number of effects on the dispersion of pollutants from a typical smelter complex.

The strong convection provides favorable conditions for dilution of effluents. However, close to the source -- even one with a tall stack -- the strong instability can produce a looping plume that will bring the stack gases down to the ground, exposing nearby receptors to irregular but high ground-level concentrations of pollutants.

The interaction between the strong daytime convection and the nocturnal pollution layer can be especially important in a valley area containing a major pollution source such as a smelter. The terrain may limit the lateral spread of the pollutant layer during the nocturnal inversion, resulting in a relatively dense accumulation of pollutants. Hence, when the daytime convection develops enough to reach the height of the pollution layer and bring the accumulated pollutant to ground level, the resulting fumigation can be much more severe than it might be in a plains area.

Wind conditions in the southwest desert area are strongly affected by terrain. The wind rose data for Salt Lake City show a good example of the directional channeling effect of topography. In valley areas wind speeds are often reduced because of the sheltering effect of the surrounding mountains. However, an opposite effect, accentuation of wind channeling resulting in higher wind speeds, sometimes occurs when the pressure gradient is oriented along the axis of a valley.

4. Northern Rocky Mountain Area. This area includes the smelter regions of Montana and Idaho. It is in many respects similar to the southwestern desert area in that the mountainous terrain is a significant factor in the estimate of air pollution potential at most of the smelter sites. The mountain-valley situation favors a strong diurnal cycle of the important diffusion factors.

In the Northern Rocky Mountains nocturnal inversions are a significant factor in the overall air pollution potential. Figures D-1 and D-2 show that in the western desert and mountain areas the maximum inversion frequencies generally occur south of the Montana-Idaho region.

The statistics on the mean MMD occurring in the Montana-Idaho region indicate a deep mixing layer during most months of the year. The fact that this region is generally cooler than the desert areas to the south is reflected in the lower values for the mean MMD.

Wind conditions in the Northern Rocky Mountain area will be affected primarily by the local topography of the site. Valleys will provide directional channeling of the wind field. The development of nocturnal inversions in the valley areas will be conducive to light winds during the night and early morning hours; however, local drainage winds governed by topography can be significant.

Effluent plume behavior in this area will have a diurnal pattern similar to that found in the desert area; namely, the formation of a polluted layer aloft during the night, followed by a fumigation condition and then by convective mixing as the midday heating results in the development of a strong mixing layer.

5. Pacific Coast. Along the Pacific Coast, air pollution potential is to a major extent determined by unfavorable inversion conditions and especially by restricted daily mixing depths. This is the classical situation identified as the "inversion lid" in Los Angeles smog episodes. The mixing depth phenomenon is illustrated by the mean maximum data in Figs. 3 to 14, where the Pacific Coast area is shown to have restricted mixing depths most of the year. This restricted mixing depth is due in a major degree to subsidence inversion conditions; however, these situations are not especially reflected by Figs. D-1 and D-2, which describe inversion conditions in the lowest 500 feet of the atmosphere. The base of the Pacific Coast inversion is typically higher than 500 ft.

Wind conditions along the Pacific Coast are dominated by the ocean-land combination, with strong directional control by topography. The San Francisco Bay Area is a good example of this as shown by Figs. D-16 and D-18, where persistent on-shore winds dominate the pattern in the summertime.

REFERENCES

1. Holzworth, G. C., Estimates of Mean Mixing Depths in the Contiguous United States, Mon. Weather Rev., 92(5), 235-242 (May 1964)
2. Hosler, C. R., Low-Level Inversion Frequency in the Contiguous United States, Mon. Weather Rev., 89(9), 319-339 (September 1961)

APPENDIX E

ZINC, LEAD, AND COPPER MARKETS

1. Zinc . . . . E - 1
2. Lead . . . . E - 9
3. Copper . . . . E - 15

ZINC, LEAD, AND COPPER MARKETS

Estimates have been made of the growth of U.S. markets for zinc, lead, and copper in the period up to 1975 and, from these, estimates have also been made of the probable additions to smelting capacity required in the same period.

Zinc

Demand for zinc in the United States is expected to increase at an annual rate of about 2.5 percent between 1965 -- the last year on trend -- and 1975. By the end of the period, therefore, demand will be 2.2 million short tons, up 458,000 tons from a 1965 consumption of 1,742,000 short tons.[1] Slab zinc has accounted for nearly 80 percent of this consumption in recent years; it is anticipated that slab zinc will continue to account for about the same percentage in 1975. Table E-1 summarizes the historical and projected demand for zinc in the United States.

As noted in the table, there are three major areas of slab zinc usage: galvanized products, zinc-based alloys, and brass products. These uses annually account for over 90 percent of the slab zinc consumed, with most of the remainder used in rolled metal products, paint, floor coverings, and chemicals. This pattern of consumption has not changed significantly in recent years. For the future, however, the intensification of the plastics threat to the die-casting market in the automotive field could alter the historical pattern. Both technical and economic factors will play a role in determining what share of this market zinc will continue to hold. On the basis of recent research and development activity by the

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[1] Both 1966 and 1967 were off-trend years; for 1966 because of inventory building in anticipation of the strike, for 1967 because of a slowdown in the economy and of the industry-wide strike that started in July. Consumptions in 1966 and 1967 were 1,807,000 and 1,566,000 short tons, respectively. Based on preliminary figures from the Bureau of Mines, consumption in 1968 is estimated to be at least 1,670,000 short tons.

Table E-1

U.S. ZINC DEMAND
(Thousands of Short Tons)

DEMAND FOR ZINC	1960	1967	1975
Slab Zinc	878	1237	1750
Ores*	88	106	150
Secondary*	193	223	300
Total Demand	1159	1566	2200
DEMAND FOR SLAB ZINC			
Galvanized Products	372	459	600
Brass Products	99	132	200
Zinc-Base Alloys	338	535	800
Other	69	111	150
Total Demand	878	1237	1750

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* Recovered zinc content.

Source: Historical—Bureau of Mines

Projection—Stanford Research Institute.

Table E-2

U.S. SLAB ZINC CONSUMPTION BY PRODUCT CATEGORY
(Thousands of Short Tons)

PRODUCT CATEGORY	1955-59 (Avg)	1960	1961	1962	1963	1964	1965	1966	1967	1975
Galvanized Products										
Sheet and strip	188.4	196.1	211.3	214.0	238.9	257.3	270.8	264.3	236.1	
Wire and wire rope	39.8	35.3	37.6	38.2	39.5	42.8	43.9	39.1	37.7	
Tubes and pipe	76.4	56.7	55.0	54.0	56.6	62.2	63.2	68.8	61.8	
All other	95.4	83.6	78.2	82.4	84.3	94.0	104.5	123.8	123.9	
Subtotal		371.7	382.1	388.6	420.3	456.3	482.4	496.0	458.6	600
Brass Products										
Sheet, strip and plate	57.0	45.9	60.0	61.2	61.5	64.7	58.9	97.1	67.2	
Rod and wire	38.6	30.0	41.0	41.9	43.5	47.2	45.5	60.1	40.8	
Tubes	12.5	8.5	10.2	10.6	10.8	10.4	10.0	12.1	8.9	
All other	14.7	14.7	17.3	16.1	12.5	12.7	12.4	16.3	14.7	
Subtotal		99.1	128.5	129.8	128.2	135.1	126.8	185.6	131.5	200
Zinc-base Alloys										
Die-casting alloy	364.6	331.1	337.2	419.0	462.5	517.4	629.8	596.4	526.0	
All other	10.1	7.2	4.5	4.6	6.1	7.2	8.1	9.7	9.2	
Subtotal		338.3	341.7	423.6	468.6	524.6	638.0	606.1	535.2	800
Miscellaneous*	80.4	68.9	78.8	60.7	88.0	91.2	106.8	122.6	111.5	150
Total Consumption	977.9	878.0	931.1	1031.7	1105.2	1207.1	1353.9	1410.2	1236.8	1750

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* Includes rolled zinc, zinc oxide and other uses—wet batteries, desilvering lead, light metal alloys, etc.

Source: Historical—Bureau of Mines.
Projection—Stanford Research Institute.

Table E-3

U.S. ZINC CONSUMPTION BY MAJOR RAW MATERIAL

(Thousands of Short Tons)

YEAR	SLAB ZINC	ORES* RECOVERED (Zinc Content)	SECONDARY RECOVERED (Zinc Content)	TOTAL
1955	1119.8	118.1	231.1	1469.1
56	1008.8	113.4	200.8	1323.0
57	935.6	110.3	185.7	1231.6
58	868.3	94.9	178.9	1142.2
59	956.2	108.1	214.1	1278.4
1960	877.9	88.3	192.8	1158.9
61	931.2	97.3	179.0	1207.5
62	1031.8	101.6	199.9	1333.3
63	1105.1	104.7	204.4	1414.2
64	1207.3	105.9	222.5	1535.8
1965	1354.1	122.9	265.1	1742.1
66	1410.2	126.7	269.6	1806.5
67	1236.8	106.1	223.1	1566.0
1975	1750	150	300	2200

---

* Consumption of ores for other than slab zinc production.

Source: Historical—Bureau of Mines
Projection—Stanford Research Institute.

industry, it is anticipated that zinc will do reasonably well in maintaining its share of the die-casting market.

Although other metals can technically replace slab zinc in many of its uses, economic substitutes for zinc in its major end-use markets are relatively limited at present. Aluminum coatings in place of zinc for steel offer a potential threat, but the present costs and certain deficiencies in the protective qualities of aluminum coatings favor zinc's retention of this market.

In the important die-casting market, plastics and aluminum compete with zinc, but have made only a modest impact to date. A major incentive to seek substitutes for zinc in this market, as well as in the galvanizing market, does not appear to exist, considering the highly favorable cost and performance characteristics of zinc. Any competitive losses that do take place are likely to be more than offset by gains made in new and expanded applications -- for example, utilization of galvanized steel, in the initial construction of bridges. Other promising market opportunities for galvanized zinc are in residential sidings and in prefabricated buildings, as well as in reinforced and prestressed concrete structures.

The estimated 1975 consumption of 2.2 million short tons, shown in Table E-1, appears reasonable in the light of a careful examination of the end use markets for zinc and of the various factors causing shifts in these markets. This figure includes an estimate of 1.75 million short tons of slab zinc, which can be compared with a U.S. Government estimate (made in 1964) of 1.63 million tons. The estimate of 1975 slab zinc consumption assumes that the zinc-base alloy sector will require roughly 200,000 tons more than was consumed in 1968. Although this assumption might be somewhat optimistic, the growth of usage in the galvanizing sector could easily be greater than shown. Thus, the errors in the estimates of individual sector consumptions will probably tend to counterbalance one another and exert a minimal influence on the estimated total slab consumption.

Mine production of zinc ore in the United States currently accounts for nearly 50 percent of the slab zinc supply. From 1958 until 1966-1967, when labor troubles caused a temporary reversal, production had been increasing gradually, and is expected to continue with steadily mounting mine production from Tennessee and New York. Mine production in the Rocky Mountains and western states is less assured and more sensitive to zinc prices, since within this area zinc is in many instances a by-product of lead-silver mining in Idaho, Utah, Montana, and Washington. Zinc mine production is also vulnerable because practically all of it comes from underground mines which will be caught in the same cost-price squeeze as lead mines. Thus, while the share of slab zinc supply from domestic ore has been increasing from 42 percent in 1960, this is likely to stabilize in the future with domestic and foreign ores each supplying about half the requirements.

Historically, about 85 or 90 percent of the slab zinc supply comes from U.S. smelters; the balance is imported. Imports of slab accounted for close to 20 percent of requirements in 1966 and 1967, but this was due to the inventory buildup in anticipation of the strike, and then to the strike itself in mid-1967. Table E-4 shows the pattern of slab zinc supply for 1960 to 1967, as well as the expected supply in 1975.

The zinc smelting and refining industry operated 15 primary (see Table E-5) and eight secondary reduction plants producing slab zinc in 1967.[2] On the basis of data from the Bureau of Mines, total capacity of reduction plants at the end of 1966 amounted to:

Primary plants	1,243,000 short tons[3]
Secondary plants	50,000 short tons

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[2] Producers of slab zinc also made zinc compounds, alloys, zinc dust, and rolled zinc.

[3] This figure does not agree with the figure in Table E-5 because of differences in reporting, but it is believed to be a reasonable check.

[4] Two factors that could limit capacity additions are: size of the Government stockpile and greater recovery of zinc from lead smelting (slag fuming, etc.)

Table E-4

U.S. SLAB ZINC SUPPLY
(Thousands of Short Tons)
1960-1975

YEAR	PRODUCTION	IMPORTS	EXPORTS	NET IMPORTS	TOTAL SUPPLY*
1960	868.2	120.8	75.1	45.7	913.9
61	902.0	127.6	50.1	77.5	979.5
62	938.3	142.0	36.1	105.9	1044.2
63	952.9	144.8	33.9	110.9	1063.8
64	1025.7	118.3	26.5	91.8	1117.5
1965	1078.0	153.0	5.9	147.1	1225.1
66	1108.4	278.2	1.4	276.8	1385.2
67	1010.7	221.4	16.8	204.6	1215.3
68	1070.0				
1975	1500			250	1750

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[*] Excluding changes in inventory

Source: Historical—Bureau of Mines
Projection—Stanford Research Institute.

Table E-5

U.S. PRIMARY ZINC CAPACITY
(Thousands of Short Tons)

COMPANY	LOCATION	PREEXPANSION CAPACITY (1/1/67)	POSTEXPANSION CAPACITY (12/31/68)
American Smelting and Refining Co.	Corpus Christi, Texas	108	108
	Amarillo, Texas	54	54
American Zinc	Monsanto, Illinois	70	84
	Dumas, Texas	55	57
The Anaconda Co.	Great Falls, Montana	162	162
	Anaconda, Montana	87	87
Bunker Hill	Kellogg, Idaho	92	110 (+18)
Blackwell Zinc	Blackwell, Oklahoma	90	90
The Eagle-Picher Company*	Henryetta, Oklahoma	54	54
Matthiessen and Hegeler	LaSalle, Illinois†	25	--
	Meadowbrook, West Virginia	50	50
National Zinc	Bartlesville, Oklahoma	42	65 (+23)
The New Jersey Zinc Company	Depue, Illinois	50	57 (+7)
	Palmerton, Pennsylvania	110	110
St. Joseph Lead Co.	Josephtown, Pennsylvania	175	175
	Total	1224	1263

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[*] It is understood that Eagle-Picher is planning to close down its Henryetta smelter early in 1969.

[†] No longer operated as a smelter (1968).

Source: American Bureau of Metal Statistics, Yearbook for 1966 and 1967; Bureau of Mines; *Metals Week*, various recent issues.

Total capacity additions -- all of them expansions of existing facilities -- during 1967 and 1968 will amount to about 50,000 short tons per year. As shown in Table E-5, the expansion will be achieved in three plants: Bunker Hill's Kellogg, Idaho facilities -- increase of 18,000 short tons; National Zinc's Bartlesville, Oklahoma facilities -- increase of 23,000 short tons; and New Jersey Zinc's Depue, Illinois facilities -- increase of 7000 short tons. The total increase, however, will be more than offset by the announced closing of Eagle-Picher's Henryetta, Oklahoma smelter in 1969. This plant has a rated capacity of 54,000 short tons per year. Thus, by the end of 1968, industry capacity will amount to about 1,350,000 short tons; but by mid-1969, at the latest, total capacity will drop to just under 1,300,000 short tons.

In order to supply the 1975 demand that has been projected for slab zinc, it is anticipated that about 350,000 to 400,000 short tons of additional annual capacity will need to be installed during the 1969-1975 period.[4] If the present pattern is followed, much of the additional capacity requirements could come from expansion of existing facilities. While it is believed this will be the most likely action taken by the companies involved, it is not unreasonable to expect that one, or possibly two, entirely new smelters might be built sometime during the next seven years. For example, if it is assumed that the capacity of each of these plants would be 50,000 short tons, some 40 percent of the required new capacity would be accounted for by new facilities. On this assumption, expansion of existing facilities would account for the other 60 percent of new capacity by 1975. Decisions on expansion of existing facilities or construction of new ones are dependent upon such factors as the availability of ore reserves and the share and location of the market.

Lead

Demand for lead in the United States is expected to increase at the rate of nearly 2 percent per year between 1965 -- the last year on trend -- and 1975. At this rate, demand by 1975 will be 1.5 million short tons, or approximately 260,000 tons greater than 1965 consumption of 1,242,000 short tons.[5] Metal products account for close to 70 percent of total use, with pigments, chemicals, and other miscellaneous items making up the balance. The pattern is not expected to be greatly different in 1975. Table E-6 summarizes the historical and projected demand for lead in the United States.

For many of its traditional uses, lead is very vulnerable to market erosion through substitutions of other materials and adverse technological change. Substantial substitution has already taken place. Plastics are being used increasingly for cable sheathing and in chemical containers, as is copper for piping. Plastics and aluminum offer serious threats to lead in various construction applications. Zinc and titanium are being substituted for lead in paint pigments and in solder.

Over one-half of the lead consumed annually goes into motor vehicle use. In 1967, approximately 37 percent of all lead consumed was used in producing automobile storage batteries, and an additional 20 percent went into gasoline antiknock additives. Both markets have shown good growth; their outlook to 1975 remains good. There is a potential threat to the gasoline additives market from possible legislative action to eliminate lead for health reasons, but this is not expected to become serious before 1975. The battery market has been, and will continue to be, a growing market.[6] However, it should be noted that lead usage in batteries has failed to keep pace with the increasing number of cars in service because of (1) longer battery life and (2) use of battery grids containing less lead. These trends will continue to affect future use of lead in batteries.

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[5] Both 1966 and 1967 were off-trend years; 1966, because of inventory building in anticipation of the strike, 1967 because of a slowdown in the economy and because of the industry-wide strike that started in July. Consumptions in 1966 and 1967 were 1,324,000 and 1,240,000 short tons, respectively. Based on preliminary figures from the Bureau of Mines, consumption in 1968 is estimated to be 1,290,000 short tons, an increase of about 4 percent from the previous year.

[6] An industry representative has recently stated that "there is no competitive system known or projected which can compete with the lead battery on an economic basis."

Table E-6

U.S. LEAD DEMAND
(Thousands of Short Tons)

PRODUCT CATEGORY	1960	1967	1975
Metal Products			
Storage Batteries	353	455	550
Other	370	384	450
	723	839	1000
Pigments	98	100	125
Chemicals			
Gasoline Additives	164	247	325
Other	3	1	--
	167	248	325
Miscellaneous	33	29	50
Total Demand	1021	1240*	1500

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* Includes 23,800 short tons undistributed consumption.

Source: Historical—Bureau of Mines
Projection—Stanford Research Institute.

The research and development program of the lead industry is designed to stimulate new uses for lead. The growing need for sound control devices offers a promising application for lead where it is necessary to reduce noise and vibration -- for example, in air conditioning systems. Lead also may be used as a shield against nuclear radiation in commercial nuclear power plants. It may also find increased use in new corrosion protection applications such as in ships, bridges, and piers.

Refined lead is produced in the United States at primary refineries and smelters that process ore (domestic and imported), base bullion (domestic and imported), and small quantities of scrap, as well as at secondary smelters that process scrap almost exclusively. During the 1960-67 period, about 45 percent of the refined lead supply came from recovery of scrap lead, roughly 30 percent from imported ore and base bullion, and the remaining 25 percent from domestic ore. From time to time, withdrawals have been made from the Government stockpile to meet demand. For the future, it is expected that secondary recovery of lead will continue to supply between 40 and 50 percent of total needs. The other 50 to 60 percent will come from smelter-refinery production based on domestic and imported ores as well as base bullion. With increasing mine capacity and production in the United States, it is likely that imported ores and base bullion will decline in the future, as U.S. smelters rely to a larger extent on domestic ore and bullion supplies.

With two new smelters coming into operation in 1968 and St. Joseph Lead expanding its Herculaneoum, Missouri smelter by over 50 percent, U.S. smelters will, by next year, be able to turn out close to 700,000 short tons of primary metal by operating at around 90 percent of capacity (see Tables E-7 and E-8 for U.S. smelter and refinery capacity). A real lead surplus could develop in the next two to three years, if domestic smelters produce near capacity and foreign suppliers of lead (pig and bars) continue to move their materials into the U.S. market at the same rate as in recent years. The industry should be able to accommodate this new primary lead capacity with minimum difficulty, although prices will probably continue to be on the soft side. However, the higher cost lead producers will continue to be squeezed between rising costs, on the

Table E-7

U.S. PRIMARY LEAD CAPACITY-SMELTERS
(Thousands of Short Tons Charge*)

COMPANY	LOCATION	PREEXPANSION CAPACITY (12/31/66)	POSTEXPANSION CAPACITY (12/31/68)
American Smelting and Refining Company	East Helena, Montana	360	360
	El Paso, Texas	360	360
	Selby, California†	192	192
	Glover, Missouri†	--	180
International Smelting and Refining Company	Tooele, Utah	300	300
Bunker Hill	Bradley, Idaho†	330	390
Missouri Lead §	Buick, Missouri	--	300
St. Joseph Lead	Herculaneum, Missouri†	360	600
	Total	1902	2682

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* Charge capacity includes ore plus flux, but excludes fuel.

† Facility is a combination smelter-refinery.

§ AMAX-Homestake joint venture.

Source: American Bureau of Metal Statistics, Yearbook for 1966 and 1967; Bureau of Mines; *Metals Week*, various recent issues.

Table E-8

U.S. PRIMARY LEAD CAPACITY—REFINERIES
(Thousands of Short Tons Refined Metal)

COMPANY	LOCATION	PREEXPANSION CAPACITY (12/31/66)	POSTEXPANSION CAPACITY (12/31/68)
American Smelting and Refining Company	Selby, California*	72	72
	Perth, New Jersey	96	96
	Omaha, Nebraska	180	180
	Glover, Missouri*	--	78
United States Smelting Lead Refinery, Inc.	East Chicago, Indiana	40	40
Bunker Hill	Bradley, Idaho*	110	110
Missouri Lead†	Buick, Missouri	--	100
St. Joseph Lead	Herculaneum, Missouri*	120	200
	Total	618	876

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* Facility is a combination smelter-refinery.

† AMAX-Homestake joint venture.

Source: American Bureau of Metal Statistics, Yearbook for 1966 and 1967; Bureau of Mines; *Metals Week*, various recent issues.

one hand, and overproduction and consequent price weakness, on the other. It seems probable that some of the older underground mines will be abandoned, but gradually rather than suddenly.

With the new smelter capacity just now going into operation, the industry will be in a position to supply the demand for new lead through at least 1975. Thus, from a supply-demand point of view, no additional smelter capacity is required in the United States. However, this does not necessarily mean that no new smelter capacity will be built. For example, one or two of the present producers may find that it is no longer economic to continue operating their obsolete smelter facilities. If such is the case, they will be faced with three alternatives with respect to replacement:

1. To modernize the existing plant, without increasing capacity,
2. To modernize the existing plant, simultaneously increasing capacity,
3. To close down the existing plant and build a new one, probably with increased capacity.

On balance, it is likely that another 50,000 to 100,000 tons of smelter capacity will be built before 1975 but that total capacity will not increase because older facilities will be shut down.

Copper

Demand for copper in the United States is expected to increase at an annual rate of slightly in excess of 3.0 percent between 1965 -- the last year on trend -- and 1975. By 1975, demand for copper will be 3.65 million short tons, or 936,000 tons more than the 1965 consumption of 2.71 million tons.[7] Refined copper accounts for roughly 75 percent of total consumption; there is no reason to believe this share will change much in the period to 1975. Table E-9 summarizes the historical

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[7] Consumptions in 1966 and 1967 were 3.1 million and 2.57 million short tons, respectively. Both years were unusual in that 1966 was an inventory building year in anticipation of the strike, and 1967 was the year of the strike itself -- one that lasted nearly 9 months. Based on preliminary figures from the Bureau of Mines, consumption of refined copper in 1968 is estimated to be 1,860,000 tons, a decrease of 4 percent from 1967.

Table E-9

U.S. COPPER DEMAND
(Thousands of Short Tons)

	1960	1967	1975
Demand for Copper			
Refined	1350	1922	2750
Scrap*	472	644	900
Total Demand	1822	2566	3650
Demand for Refined Copper			
Wire mills	829	1240	1700
Brass mills	486	650	1000
All other	35	32	50
Total Demand	1350	1922	2750

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* To brass mills (80 to 85 percent) and to foundries and chemical plants (15 to 20 percent).

Source: Historical—Bureau of Mines
Projection—Stanford Research Institute.

and projected demand for copper in the United States.

There are two principal consumers of refined copper: wire mills and brass mills. Together, these two sectors account for 97 or 98 percent of total refined copper use.[8] The other 2 to 3 percent of refined copper is consumed by foundries, chemical plants, and other miscellaneous industries.[9] The relative use of copper by different consuming sectors, and the relative consumption of refined and of scrap copper, appear to have changed very little in the past decade. No appreciable change is expected during the next decade.

While copper will continue to be subjected to considerable competitive pressure both from other metals (aluminum primarily, but also stainless and galvanized steel) and other materials (plastics, primarily) in the next several years, copper is also expected to make some significant competitive moves of its own. The industry, through the Copper Development Association, has two objectives in mind: (1) to prevent further inroads by other metals into electrical and some industrial applications; and (2) to make further gains for copper in the fields of transportation and construction. To a considerable extent, these objectives are being accomplished with such research developments as new copper alloys, cladding materials with copper, and the like. Markets at stake, to name the most important, are the wire business, the automobile radiator business, and the home plumbing business. On balance, copper may lose position in some of its major markets, but the outlook for improving its position in others is very encouraging; sufficiently so that no major downward shifts in the important copper use sectors are anticipated.

About 65 percent of total U.S. copper supply, refined and scrap, comes through the mine-smelter-refinery route; the balance is provided from scrap itself. In terms of smelter operation, mine production of copper ore (metal content basis) gives a close approximation of the amount of metal which is then charged to the smelters. The following tabulation shows this relationship for the 1960-66 period:

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[8] It should be noted that refined copper taken by brass mills is only about 55 to 60 percent of the total copper used; the balance is provided by copper scrap.

[9] These miscellaneous uses rely to a much greater extent on copper scrap than on refined copper; the ratio is roughly three-quarters to one-quarter.

	1960	1962	1964	1966
	(Thousands of Short Tons)			
Primary New Copper Produced[*]				
By mines	1080	1228	1247	1429
By smelters	1142	1282	1301	1430
Total Primary Copper Produced[**]	1308	1410	1427	1581

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[*] From domestic ore as reported.

[**] From domestic ore as well as from foreign ore and secondary sources (scrap).

The copper smelting industry operated 16 smelters in 1967, with a total charge capacity of about 8.5 million short tons (see Table E-10). There was virtually no change in the nominal smelting capacity in the ten years before 1968, but the annual production of copper increased by about 300,000 short tons in the same period. In 1966, the peak year of smelter production, the industry turned out a total of 1,58 million short tons of copper -- 1.43 million tons from domestic ore.

Over the past 15 years there have been large increases in mine production, partly from major expansions of some of the larger existing properties, but mainly from the opening of new mines. These new mines have been opened in Arizona, Colorado, Montana, Nevada, and Michigan. Currently, operations are being expanded in all of these areas, and in Utah as well. Plans have already been announced for increasing mine production by the early 1970's by the equivalent of 375,000 short tons of metal per year. It is estimated that by 1975 a further 125,000 tons per year of equivalent metal output will be added, making the total increase in mining capacity between now and 1975 equal to 500,000 tons of metal per year.

Table E-10

U.S. COPPER SMELTERS
(Thousands of Short Tons Charge*)

COMPANY		
Asarco	El Paso, Texas	420
Asarco	Hayden, Arizona	420
Asarco	Tacoma, Washington	600
Anaconda Company	Anaconda, Montana	1000
Inspiration Consolidated Copper Co.	Miami, Arizona	450
Magma Copper Company		
Magma Division	Superior, Arizona	150
San Manuel Division	San Manuel, Arizona	403
Kennecott Copper Corp.		
Nevada Mines Division	McGill, Nevada	400
Chino Mines Division	Hurley, New Mexico	400
Ray Mines Division	Hayden, Arizona	420
Utah Copper Division	Garfield, Utah	1000
Phelps Dodge Corp.		
Douglas Smelter	Douglas, Arizona	1250
Morenci Branch	Morenci, Arizona	900
New Cornelia Branch	Ajo, Arizona	300
Tennessee Corporation		
Tennessee Copper Co. Division	Copperhill, Tennessee	90
Total		8203
White Pine Copper Co.	White Pine, Michigan	90†
Total		90†

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[*] Stated in tonnage of capacity for smelting materials that yield a product.

[†] Thousands of tons of copper.

Source: American Bureau of Metal Statistics, Yearbook for 1967.

New smelting capacity or other reduction facilities will have to be provided to handle this increased metal production. A substantial fraction of the added output of metal may be produced by use of new hydrometallurgical processes that avoid smelting entirely. However, major expansions of conventional smelting capacity have been announced for existing smelters -- American Smelting and Refining Co. at Hayden, Arizona; Kennecott Copper Corp. at Hayden, Arizona and Garfield, Utah; Magma Copper Co. at San Manuel, Arizona; Phelps Dodge Corp. at Morenci, Arizona; White Pine Copper Co. at White Pine, Michigan; Inspiration Consolidated Copper Co., Inspiration, Arizona. The total capacity increase required is such that one or two new smelters might be constructed, but expansion of existing smelters appears to be the present course of action.

APPENDIX F

MARKETS FOR SULFUR AND SULFUR BY-PRODUCTS

1 Introduction . . . . F- 1

2 World and U.S. Sulfur Markets . . . . F- 3

3 Regional Markets for Sulfur and Selected Sulfur Compounds F-15

4 Existing Markets for Sulfur By-Products from Smelters F-33

5 Future Markets for Sulfur By-Products from Smelters (1975) F-63

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APPENDIX F-1
INTRODUCTION

The production costs of five processes for removal of sulfur dioxide from smelter gas have been examined as part of this project. All but one of these processes recovers the sulfur dioxide in a salable form: as sulfur, liquid sulfur dioxide, sulfuric acid, or ammonium sulfate. Calcium sulfate waste is the product from the fifth process. Other processes not examined during the project but that might be feasible also recover salable by-products, e.g., sulfuric acid from Monsanto's Catox process and liquid sulfur dioxide from Wellman Lord's proprietary process.

The economic feasibility of four of the five processes studied and of the other possible processes depends not only on the production costs but also on the quantity of the recovered product that can be marketed and the price it can command in that market.

Therefore, the purpose of the market study portion of the project is to estimate the amount of each of the four sulfur by-products from smelters, i.e., sulfur, sulfur dioxide, sulfuric acid, and ammonium sulfate,* that might be sold and the probable selling price of each product. This market information is incorporated with the data from the other phases of the project to indicate:

- Which by-products appear to have the best opportunity of finding markets
- The cost levels that must be achieved in the process (or processes) used to make the products so the smelter operator might consider installing the process.

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* Henceforth in this Appendix to the report the term "smelter by-product" refers specifically to the above four materials.

This market study has been divided into four tasks:

1. To estimate the present and future (1975) world and U.S. supply, demand, and price for sulfur.
2. To estimate the present supply, demand, and price for sulfur by-products from smelters in the market areas surrounding the smelters, where the by-products might be sold.
3. To estimate the amounts of these smelter by-products that might be sold in these market areas under current demand-supply situations and the price ranges determined in the first two tasks.
4. To identify and, to the extent possible, quantify future markets that might develop for these by-products.

The Chemical Process Industries Economics Group in the Economics Division of Stanford Research Institute was responsible for the market research. Dr. William T. Sutphen is the Group Manager and provided the administrative direction. Mr. F. Alan Ferguson was the project leader. Mr. S. A. Cogswell, Mr. John M. Warner, and Mrs. Joan MacKenzie of the CPIE Group and Dr. James Christianson from the Life Sciences/Division all provided valuable inputs as members of the project team.

APPENDIX F-2
WORLD AND U.S. SULFUR MARKETS

The prices of the smelter by-products that are produced and the quantities that can be sold are affected by world sulfur prices because sulfur is an item of international commerce. World prices, in turn, are primarily determined by the world supply of and demand for sulfur. Therefore, estimates of future world and U.S. supply, demand, and price are essential to the market portion of this study.

Sulfur Sources

Sulfur is available in a number of forms and from a variety of sources. Elemental sulfur is mined from Frasch wells and other native deposits or is recovered from natural gas or gaseous oil refinery streams that contain hydrogen sulfide. Pyrite (FeS_2) is an important source of sulfur which is usually converted first to sulfur dioxide, then to sulfuric acid. Nonferrous smelter gases are also a significant source of sulfur dioxide, which is converted primarily to sulfuric acid. Lesser sources include gypsum, which can be treated to yield sulfur or sulfur dioxide and lime or cement, and sulfuric acid sludge from refineries, which is burned to recover the sulfur values and then converted to new sulfuric acid.

Table F-1 contains data on the worldwide and U.S. sources of sulfur in all forms in 1965 and estimates of the quantities of sulfur that could be produced from these sources in 1975.

Total world production in 1965 from all sources was 28.8 million long tons* of sulfur equivalent. The same year, U.S. production was just over 9 million long tons. The potential production in 1975 -- 53.4 million long tons in the world and 16 million long tons in the United States --

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* All sulfur quantities in this report are expressed in long tons (2,240 pounds). The quantities of all other by-products and commodities are expressed in short tons (2,000 pounds).

Table F-1

SULFUR SOURCE DATA

Source	Production (1965) (1,000 long tons/yr of sulfur or sulfur equivalent) Worldwide	Production (1965) (1,000 long tons/yr of sulfur or sulfur equivalent) U.S.	Potential Future Production (1975) (1,000 long tons/yr of sulfur or sulfur equivalent) Worldwide	Potential Future Production (1975) (1,000 long tons/yr of sulfur or sulfur equivalent) U.S.
New Sulfur				
Primary Source				
Frasch Native	7,630	6,120	13,000*	10,000*
Pyrite	9,680	350	14,000	700
Other Native	1,950	negl.	3,000	negl.
By-Product Source				
Elemental Sulfur from:				
Natural Gas	5,570	660	12,400	1,100
Crude Oils		840†	4,500†‡	1,200†
Pyrite from Coal	0	0	negl.	negl.
Sulfur Dioxide from:				
Smelter Gases	2,500	390	4,500*	1,000
Power Plant Gases	0	0	greater than 2,000*	500
Gypsum or Anhydrite	800	0		500
Subtotal	28,130	8,360		15,000
Secondary (Used) Sulfur from:				
Refinery Acids	700	700		1,000
Total	28,830	9,060	53,400	16,000

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* Production could easily increase another million tons, if demand warrants.

† Includes H_2S (from refinery stacks) that is converted directly to H_2SO_4.

‡ Includes sulfur from processing of tar sands.

was estimated after analyzing and assessing each major source to determine to what extent production might be expanded. The estimates are based not only on the ability of the current suppliers (and potential new suppliers) to increase production but also on the Institute's assessment of the feasibility of their doing so. For example, most of the sulfur emitted to the atmosphere in the form of sulfur oxides comes from the combustion of coal and oil. Existing and planned air pollution control regulations will require that users of coal and oil reduce the amount of sulfur oxides they emit. Recovery of the sulfur, in some salable form, would be one way of reducing the emissions and would then result in a new source of sulfur to be added to the potential future production. However, since the cost of recovering the sulfur being emitted by the fuel users other than utilities is relatively high and since alternative, less expensive methods of complying with most regulations are available to them, the Institute project staff are of the opinion that no significant quantities of sulfur will be recovered from this coal and oil at least before 1975. Therefore, sulfur from combustion gases, other than from large power plants, is not included in Table F-1.

Similar analyses were made for each existing and potential source of sulfur. The following are brief recapitulations of these analyses of each major sulfur source and the essential conclusions reached about the amount of sulfur that will be produced from each.

Frasch sulfur is the traditional and, at a production cost of around \$10/ton or less, is probably the least expensive source of elemental sulfur, although Frasch recovery costs have been increasing relative to the cost of recovering sulfur from natural gas. Frasch sulfur production was 7.6 million long tons in 1965 or 26% of the 28.8 million tons produced. In 1967 it did not appear that production of Frasch sulfur could be expanded more than 50% over the 1965 production, even by 1975. However, since then, Duval Mining Corporation and other companies have announced plans to develop large sulfur deposits in Pecos and Culberson Counties, Texas. These deposits apparently differ from conventional Frasch deposits in that the caprock normally extending over the sulfur deposit is not present. However, they will be mined by the Frasch process (hot water injection) so they have been classified as Frasch rather than native sulfur deposits. Production from these deposits in West Texas and from the other Frasch mines should reach 13.0 million long tons by 1975, or nearly 170% of the 1965 figure. Also, if demand warrants, production could probably be increased by another million tons/year.

Sour natural gas is the next most important source of sulfur in the world; at least in terms of quantity of production combined with a low production cost of somewhere around $12 per long ton. In 1965 sulfur recovered from this source and from refineries provided about 5.6 million long tons of sulfur. Large increases in production are expected from the western Canadian provinces with some increase from the United States, very little more from the Lacq gas fields in France, and more from the Middle East where sour gases are already slated to supply an additional 1.3 million long tons.

The 1965 data were not complete enough to allow the division of the recovered elemental sulfur figure into that from natural gas and from refineries. In 1967, however, the data on recovered sulfur are more complete and it appears that at that time about three-quarters of the total came from natural gas and one-quarter from refineries.

The recovery of sulfur from gases with high hydrogen sulfide contents could increase the amount of sulfur recovered from sour natural gas in the future. Plants handling natural gas that contains 35% or more hydrogen sulfide are now in operation, whereas 15% was the maximum in the gas handled just a few years ago. Furthermore, it is entirely possible that gases with 75% hydrogen sulfide or even more may be processed in the near future. Such a development would not only mean that more sulfur would be recovered per unit of gas, but also that sulfur from gas would no longer be a by-product but rather an independent source that could be expanded or contracted, independent of any changes in the demand for natural gas. With these changes taking place, it appears that sour natural gases in the world could provide 12 million long tons per year of sulfur by 1975 if the market requires it. Production of sulfur or sulfur equivalent from refineries could also increase to about 4.5 million long tons by 1975.

Native, non-Frasch sulfur has become an important sulfur source, particularly in Eastern Europe. Poland is now producing native sulfur and selling it to noncommunist countries in competition with Frasch and recovered sulfur. Production of native sulfur -- primarily in the communist countries, including Poland -- will probably increase from an estimated 1.9 million long tons (1965) to three million long tons by 1975.

Gypsum, or anhydrite, and sludge acids from oil refineries account for less than 1 million tons each of the world's total sulfur supply. Neither of these sources can provide sulfur (as sulfuric acid) as inexpensively as the more important sources of sulfur. Gypsum and the related spend-oxides are used in processes to make acid in areas where other forms of sulfur are relatively expensive, such as in England. Much of the refinery sludge acid, which is reburned to make fresh acid, is processed in the United States.

No specific projections were made of the future use of these as sources of sulfur, but no large growth in use can be expected. In the case of sludge acid, it appears that nearly 80% of the acid currently consumed by U.S. refineries, primarily for alkylation, is returned to the acid plant and reburned or is reused to make fertilizers. If the recycle is 80%, added sulfur from this source in this country is limited to the increase from increased alkylation. Foreign refineries do not seem inclined to recover sludge acid, partly because they do not use as much acid for alkylation, so here too the chances for increased recovery seem relatively small.

The recovery of sulfur or sulfur products from coal or from waste gas resulting from the combustion of coal or oil could provide another large source of sulfur, particularly when air pollution control regulations are passed to reduce the sulfur contents of these combustion waste gases. For example, an estimated 7.4 million long tons of sulfur was released in the form of gaseous oxides from the coal burned in the United States in 1966. However, very little of this sulfur will be recovered in any form before 1975 because:

The sulfur equivalent in pyrite used in 1965 to make sulfuric acid, liquid sulfur dioxide, and some elemental sulfur was an estimated 9.7 million long tons, greater than the amount from any other single source. Production of pyrite increased only about 2% per year between 1960 and 1965, well below the 4.5% average increase for all forms of sulfur. However, the use of pyrite is apt to increase at a greater rate in the future (4% per year) for at least two reasons. First, the low growth rate in the 1960s resulted in part from competition with very low priced sulfur ($15 to $20 per long ton, U.S. Gulf Coast), and the competitive position of pyrite is obviously improved at today's sulfur prices ($38 to $40 per long ton, U.S. Gulf Coast). Second, some of the major pyrite-producing countries, most notably Spain, are developing chemical industries that consume significant quantities of sulfur. These countries will use their own pyrite to provide this sulfur regardless of the world sulfur price. This use by the pyrite-producing nations will probably continue to increase at an even greater rate than the world's total use of sulfur in all forms (Japan is the only major pyrite user that might reduce its consumption). Therefore, it appears that the use of pyrite could increase to around 14 million long tons of sulfur equivalent by 1975.

Smelter gas provided the equivalent of about 2.5 million long tons of sulfur in 1965, mostly in the form of sulfuric acid, although elemental sulfur, sulfur dioxide, ammonium sulfate, and ammonium bisulfate were also produced. The total sulfur equivalent available from nonferrous smelter operations throughout the world is roughly 15 million tons a year. Smelter gas in many situations is a source of sulfur as low in cost (in the form of sulfuric acid) as Frasch or recovered sulfur. For example, sulfuric acid can be made for about $4.50-$5.00/ton in a large contact acid plant using elemental sulfur costing $10/long ton. Large smelters with waste gases containing 6-7% sulfur dioxide can also produce sulfuric acid for around $5.00/ton. More smelter gas would be used except that many of the smelters are located too far from the industrial centers that require sulfuric acid. Even so, about 4.5 million tons of sulfur or sulfur equivalent will come from the world's smelter gases by 1975.

- Air pollution control through recovery of sulfur dioxide liberated during fuel combustion is not apt to be practiced very soon in any major foreign countries with the possible exception of Japan.
- Most of the fuel users in the United States still have more economical ways of reducing the emission, such as purchasing fuel that contains less sulfur.

Therefore, 300,000 to 500,000 tons/year of sulfur or sulfur equivalent may be available by 1975 from the processing of coal before combustion and from recovery of the sulfur values in the combustion gases.

As indicated in the preceding discussion, it appears that world sulfur sources could provide about 55 million long tons of sulfur by 1975. This potential increase -- from 28.8 million long tons in 1965 to 55 million long tons in 1975 -- is nearly a 7% annual growth rate in production. Similarly, the potential increase in production of sulfur in the United States from 9 million to at least 15.8 million tons represents an annual increase of nearly 6%. Whether or not these potential increases in production of sulfur will be adequate to meet demand will, of course, depend on how fast the demand for sulfur increases.

Sulfur Demand

The uses for sulfur and sulfuric acid are even more varied than the sources. Elemental sulfur is used as a raw material for making sulfuric acid, sulfur dioxide for pulping of wood, and a variety of sulfide chemicals. It is also used directly in agriculture as an insecticide and as a soil additive to increase crop yields from sulfur-deficient soils. About one-half of all sulfuric acid is used for solubilizing the phosphate in phosphate rock to produce phosphate fertilizer, but it has many other uses, i.e., as an alkylation catalyst for refining crude oil, to clean (pickle) steel products, as a reagent for converting ilmenite into titanium dioxide pigment and fluorspar into hydrogen fluoride, and as a raw material in the production of a host of important sulfate chemicals.

The estimated present and future (1975) consumption of sulfur by major end use is given in Table F-2 for both the world and the United States. The end uses have been subdivided into those where the sulfur is used as sulfuric acid and those where the sulfur is either in the elemental form or as sulfur dioxide. Each of these uses was evaluated in detail in order to estimate the quantity of sulfur that might be required in 1975. Among the factors considered in the evaluations were:

- Historical growth rates of the product or use that requires sulfur
- Changes that would affect the growth rate of the product (or use) in the future, such as competing materials or processes
- Changes that would affect the use of sulfur in the manufacture of the product such as alternate, nonsulfur-using methods of production.

Based on the data considered, future growth rates were estimated for each product and for the use of sulfur to make it. These growth rates were used to estimate sulfur requirements for each product shown in Table F-2. According to these estimates, world sulfur consumption should increase from the 29.5 million long tons in 1965 to 45.8 million long tons in 1975, an average annual growth rate of 4.5%, about the same growth rate that sulfur has experienced for the past 40 years. The consumption of sulfur in the United States is expected to increase from 8.1 million long tons to 11.7 million long tons, or 3.5% a year in the same 10-year period.

Enough information is available regarding the production costs, markets, and potential competitive materials to project future sulfur consumption by end use with a reasonable degree of confidence. However, a possible exception is the use of sulfur for the manufacture of phosphate fertilizers. The Institute's estimate of increased sulfur use for phosphate fertilizer production in the world -- from 3.9 million tons in 1965 to 8.0 million tons in 1975 -- is based on what is believed to be the maximum rate at which the world can assimilate the increased production of fertilizers. Considerable effort is being directed by governmental and

Table F-2

SULFUR CONSUMPTION DATA*

Major End Use for Production of:	Net Quantity Consumed (1965) (1,000 long tons/yr of sulfur or sulfur equivalent)		Estimated Future Consumption (1975) (1,000 long tons/yr of sulfur or sulfur equivalent)	
	Worldwide	U.S.	Worldwide	U.S.
Sulfur used as H_2SO_4				
Fertilizers				
Phosphoric-acid Derived	3,990	2,320	8,000†	3,900
Normal Superphosphate	4,000	600	5,100	400
Ammonium Sulfate‡	4,000	610	6,100	700
Other Fertilizers	§	230	§	650
Titanium Dioxide	1,600	520	2,000	500
Cleaned Steel	700	310	700	250
Cellulosics	2,000	255	2,500	250
Hydrogen Fluoride	350	179	680	300
Aluminum Sulfate	500	171	800	250
Surface-Active Agents	175	77	300	100
Uranium and Copper	600	190	820	400
Petroleum Refining	7,405	723	12,600	2,400
Other Materials		715		
Subtotal	25,320	6,900	39,600	10,100
Sulfur used as SO_2 or S				
Wood Pulp		600		600
Sulfide Chemicals		330		550
Other		270		450
Subtotal	4,200	1,200	6,250	1,600
Total	29,520	8,100	45,850	11,700

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* Includes all forms of sulfur.

† Lower estimates. Greater fertilizer use would increase sulfur consumption for fertilizer production from 19,200,000 to 24,150,000 tons.

‡ Both direct and by-product production.

§ Included as part of Fertilizers, Phosphoric-acid derived.

worldwide agencies to increase the use of fertilizers in the developing countries. However, increasing the fertilizer use is not simply a matter of increased fertilizer production, which would be relatively easy to achieve. Many difficulties, such as moving the fertilizer to the market, gaining the confidence of the indigent farmer, even gauging actual impact of fertilizer on the crop yields in remote areas, must be overcome before the use of fertilizers in these countries will have a significant effect on the worldwide use of sulfur to make fertilizers. It is conceivable that the agencies concerned will be successful in overcoming these difficulties. If so, use of sulfur for production of fertilizer could be as high as 24.2 million tons by 1975 instead of the projected 19.2 million tons, and total sulfur consumption in the world would approach 50.8 million long tons in 1975. In this case the average annual growth rate in consumption for the 10-year period, 1965-1975, would be 5.5%.

Sulfur Prices

Projections indicate that sulfur supplies could exceed demand in the period between now and 1975. In the past when such potential imbalances have developed, sulfur prices have fluctuated over rather wide ranges. For example, in the late 1950s, large new supplies of recovered sulfur from Canada and France, and Frasch sulfur from Mexico created an excess supply situation. As a result, elemental sulfur could be purchased in the early 1960s for $15/long ton f.o.b. U.S. Gulf Coast. (A majority of the elemental sulfur used in the world has come from along the Gulf Coast, so prices are usually related to the Gulf Coast price.) As markets developed for these new sources, sulfur demand exceeded supply so that by early 1968 the price of sulfur had increased to over $40/long ton.

The chances for a recurrence of the 1950-1960 price cycle can be estimated by comparing the magnitude of the potential imbalance between supply and demand. The developed data on potential 1975 production and consumption of sulfur are summarized on the following page.

	Million Long Tons of Sulfur or Sulfur Equivalent World	 U.S.
Potential supply (1975)	53.4-55.4	15.8-16.8
Estimated demand (1975)	45.8-50.8	11.5

As can be seen, if all of the sulfur potentially available is produced and consumption does not exceed the minimum values predicted, world supply could exceed demand by nearly 10 million tons/yr and the imbalance in the United States would be over 5 million tons/yr. This imbalance is not too serious since a sizable portion of the sulfur produced in the United States has traditionally been exported. However, the threat of a potential world imbalance of 10 million tons/yr should tend to depress the present $38-42/long ton sulfur price f.o.b. Gulf Coast. Even if the potential imbalance is only 2.6 million long tons -- resulting from minimum potential production and maximum consumption -- sizable price reductions can still be expected. Such reductions would probably occur gradually because stockpiles of sulfur are so badly depleted at the present time that several years will be required before the stocks are replenished. The only way that the price of sulfur could be maintained near its present level would be if production were only expanded enough to fill the increased demand. This is not likely to happen because the financial returns at current sulfur prices are too attractive to those companies that would develop some of the large new sulfur sources such as Canadian sour natural gas and, presumably, the West Texas deposits.

Therefore, the price of sulfur will almost certainly decline in the period between now and 1975. Just how much it is reduced will depend on the attitudes and business philosophies of the existing and potential producers. However, we believe that a good, average price for sulfur in the 1968-75 period is $30/long ton f.o.b. Gulf Coast. It is entirely possible that prices will drop below $30/long ton, but such prices should not be in effect for any extended period of time. A return to the $15/long ton price of the early 1960s is extremely unlikely because few producers can make any profit at that price and many, including the Canadian producers, would be operating at a loss.

APPENDIX F-3
REGIONAL MARKETS FOR SULFUR AND SELECTED SULFUR COMPOUNDS

With data on the overall world and U.S. supply, demand, and price situation for sulfur as a background, the next step is to relate this information to the situations that exist in the regions around the smelters and to the specific sulfur compounds that might be produced by the smelters.

For this portion of the market analysis, the United States has been divided into an eastern and a western region with the division occurring along the Mississippi River. Seven of the smelters surveyed are located in five states in the eastern region, and 26 smelters are located in 12 states in the western region. (Three on the original list of 37 smelters are not operating and one smelter reportedly had no emissions.)

Eastern Region

The data on sulfur oxides emission collected from the smelters during this study show that, while the seven smelters in the eastern region produce 12.8% of the total sulfur dioxide from nonferrous smelters, they account for only 2.6% of the total sulfur oxides emitted to the atmosphere, as shown below.

Estimated Total Sulfur Emissions from
U.S. Nonferrous Smelters

	Emissions	
Regions	Quantity (1,000 long tons sulfur equivalent)	Percent of Total
Eastern region (7 smelters)	45	2.6%
Western region (26 smelters)	1,671	97.4

Also, five of the seven eastern smelters that emit sulfur dioxide already produce sulfuric acid. According to the survey data, 926,000 tons of sulfuric acid were produced at these five smelters. If the total sulfur dioxide now being emitted from all six smelters was converted to sulfuric acid, production would only be increased to 1.08 million tons, or by about 16%.

Since the five smelters already have established marketing channels for sale of sulfuric acid (and sulfur dioxide), the increase in acid production that would correspond to complete elimination of the emissions is relatively small, and since the quantity of sulfur dioxide actually being emitted from smelting operations is so small, a market analysis of the eastern region does not seem to be needed or justified. The marketing analysis, therefore, has emphasized the western region where most of the emissions occur.

Western Region

Not only do the smelters in the western region produce the majority of the sulfur oxides, but only about 22% of this production is recovered, as shown below:

	Current Disposition of Sulfur Produced at Western Smelters	
	Thousand Long Tons/Yr of Sulfur Equivalent	Percent of Total
Emission to atmosphere	1,671	78.1%
Recovered as sulfuric acid	464*	21.7
Recovered as sulfur dioxide	4	0.2
Total sulfur oxides production	2,139	100.0%

Four possible smelter by-products, i.e., elemental sulfur, sulfuric acid, liquid sulfur dioxide, and ammonium sulfate or bisulfite, are sold in the western region. The determination of the current sources and amounts of each of these products and the location of their major markets within the region are essential in determining how much of the 1.67 million tons of sulfur equivalent in the emissions might be recovered and sold. The potential markets for each of the salable products are discussed in following sections.

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* Corresponds to 1.55 million short tons/yr of 100% sulfuric acid.

Sulfur

Table F-3 contains data on the amounts of sulfur, by type, that were available for use in the western region in 1965. Of the 7.78 million long tons of sulfur produced in the region, plus the 0.82 million long tons of Frasch sulfur made available for use from existing stockpiles, 94% (8.09 million long tons) was elemental sulfur, 2.7% (230,000 long tons) was new sulfur in other forms, and 3.1% (280,000 long tons) was secondary sulfur (refinery sludge acids).

However, 6.35 million long tons or 78% of the elemental sulfur produced were exported from the region while only 0.45 million long tons were imported (by-product sulfur from Canadian sour natural gases). This large net export of elemental sulfur shifts the relative percentages of sulfur available for consumption, as shown below.

	Available for Consumption	
	1,000 Long Tons	Percent
Elemental sulfur (new)	2,220	81.2%
New sulfur in other forms	229	8.6
Secondary sulfur	280	10.2
Total	2,729	100.0%

Essentially none of the latter two forms of sulfur was either exported from or imported to the region.

Table F-4 shows the estimated consumption of the available sulfur in the 22 western states, divided by major end use. Of the total estimated consumption of 2.63 million long tons, 2.2 million long tons or 85% of

Table F-3

SULFUR SOURCE DATA[*]
22 Western States
1965
(1,000 long tons of sulfur or sulfur equivalent)

Source	Production	Producer's Stock Changes	Exports[†]	Imports[†]	Net Available[‡]
New sulfur					
Elemental					
Primary source					
Frasch native	6,116	+822[§]	-6,348[§]	0	590
Other native	negl.				
By-product source					
Natural gas	641			479	1,120
Crude oils	510	0			510
Other forms					
Primary source					
Pyrite	23				23
By-product source					
Sulfur dioxide from smelter gas	206		0		206
Gypsum or anhydrite	0				
Secondary (used sulfur from refinery acids)	280				280
Total (all forms)	7,776	+822	-6,348	479	2,729

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[*] Includes all forms of sulfur. Blank spaces indicate that data are not available.

[†] Exports from and imports to the western United States.

[‡] Net available sulfur represents production ± stock changes, minus exports, plus imports, which should equal consumption.

[§] Includes by-product elemental sulfur.

Table F-4

SULFUR CONSUMPTION DATA*
FOR 22 WESTERN STATES
1965

Major End Use	Estimated Consumption (1,000 long tons of sulfur or sulfur equivalent)	Percent
Sulfuric acid	2,239	85.0%
Wood pulp	167	6.3
Synthetic rubber	106	4.0
Sulfide chemicals (including sulfur dioxide)	14	0.5
Other (agricultural)	107	4.1
Total*	2,633	100.0%

the sulfur were consumed as sulfuric acid.[†] About 1.7 million long tons of elemental sulfur were used in the region to make sulfuric acid plus all but about 4,000 of the 229,000 tons of new sulfur in other forms and all the 280,000 tons of secondary sulfur.

The other 15% of the sulfur (0.39 million long tons) was consumed either as elemental sulfur or in the production of sulfur compounds other than sulfuric acid. About one-third of the 0.39 million tons was used to make sulfurous acid for the production of wood pulp, one-third for vulcanization of synthetic rubber, and one-third as agricultural sulfur and for

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[*] Includes all forms of sulfur.

[†] It should be noted that the estimated consumption of sulfur (2.63 million long tons) does not match the net available sulfur reported for the western region (2.72 million long tons). The most likely reason for the 90,000 long tons difference is increases in stocks of the sulfur consumers. However, the difference between estimated consumption and net availability of sulfur is less than 4%--well within the margin of error expected in an analysis of this type.

production of sulfur-containing chemicals, including liquid sulfur dioxide. Only 14,000 long tons of sulfur were used to make all the sulfur-containing chemicals, including 7,500 long tons for liquid sulfur dioxide.

A state-by-state breakdown of the sulfur production, consumption, and, in most cases, approximate prices within the western region is provided in Table F-5. Data are also presented on the amount of sulfur available in each state in elemental and in all other forms (including secondary sulfur).

Since a large proportion of the elemental sulfur production is already exported out of the region, it can be assumed that elemental sulfur used in the region can be displaced by alternative sources of sulfur (smelter sulfur). Conversely, the sulfur in all other forms, since it is not exported, should probably be considered nondisplaceable. On the basis of the data in Table F-5 and the recognition that all of the non-elemental sulfur produced in the region is consumed there, about 81% of the sulfur consumed in the western region can be considered displaceable and the remainder (19%) nondisplaceable. This information regarding displaceable versus nondisplaceable sulfur will be used later to estimate the portion of the market in each state that is available to sulfur from smelters.

Sulfur was produced in some form in 17 of the 22 western states in 1965 as shown below:

Sulfur Form	Number of Western States Where Sulfur is Produced
Elemental only	5
Other forms only	7
Both elemental and other forms	5
Total	17

Essentially all of the western sulfur was produced in Texas (4.2 million tons) and Louisiana (3.6 million long tons). No more than 100,000 long tons was produced in any of the 15 remaining states except California,

Table F—5

SULFUR PRODUCTION, CONSUMPTION, AND PRICE DATA, BY WESTERN STATE
(1,000 long tons of sulfur or sulfur equivalent/year, except where noted)
1965

Subregion—State	Production		Exports*	Imports*	Estimated Consumption†	Price Range‡ ($/long ton)
	Elemental	Other Forms				
North West Central						
Minnesota	33	0	13	25	45	
Iowa	0	0	0	22	26	
Missouri	0	0	84	241	157	$48—50
North Dakota	32	0	32	0	0	
South Dakota	0	0	0	0	0	
Nebraska	0	0	0	0	0	
Kansas	0	12	0	53	65	48
South West Central						
Arkansas	29	5	0	31	66	41—45
Louisiana	3,589§	33	3,881	616	344	41
Oklahoma	0	28	0	27	54	42—45
Texas Panhandle	109	0	3,375	23	806	41
Central Texas	324	0				
Texas Gulf	3,548§	208				

Table F-5 (concluded)

Subregion--State	Production		Exports*	Imports*	Estimated Consumption†	Price Range‡ ($/long ton)
	Elemental	Other Forms				
Mountain						
Montana	20	27	19	0	28	§-44
Wyoming	57**	0	36	6	27	$41
Colorado	0	15	0	8	23	42
New Mexico	18**	0	0	23	37	44-51
Idaho	0	29	0	103	132	46-48
Utah	0	81	0	8	90	§-51
Arizona	0	23	0	39	59	49-61
Nevada	29**	0	0	0	29	††
Pacific						
Washington	0	27	4	113	137	§-48
Oregon	0	0	30	62	32	46-50
California	124	200	14	219	477	51-52

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* Elemental sulfur only.

† Consumption based on use, not availability.

‡ Approximate 1967 prices of sulfur in elemental form only.

§ By-product sulfur, consumed in captive operation; no minimum price is available.

** Includes stock changes.

†† Native sulfur, consumed in captive operation; no price is available.

and even there the production (324,000 long tons) was less than 10% of that produced in each of the two major producing states.

Consumption of sulfur was not concentrated nearly so much in Texas and Louisiana. To begin with, three states (Iowa, Missouri, and Oregon) that do not produce any sulfur consumed a total of 215,000 long tons. And whereas the most sulfur was still consumed in Texas (806,000 long tons), the next largest consumption occurred in California (447,000 long tons), with Louisiana third at 344,000 tons. All told, over 1,000 tons of sulfur in some form was consumed in each of 19 of the 23 western states. The three states with less than 1,000 tons of reported sulfur consumption were North Dakota, South Dakota, and Nebraska.

The 1967 prices for sulfur ranged from around $41 to over $60/long ton in the western states with the prices being highest in the Pacific Coast states, Arizona, and the states in the North West Central region.

Sulfuric Acid

Nearly 7.5 million tons of sulfuric acid was produced in the 22 western states in 1965. The production and the forms of sulfur used in the production of the acid are shown in Table F-6. Shipments of acid to and from the region were relatively small as would be expected of an abundant, low-cost commodity such as sulfuric acid. Only 270,000 tons passed over the borders of the region with exports exceeding imports by 80,000 tons. The net acid available for consumption within the region was almost 7.4 million tons.

The end-use pattern is shown in Table F-7. As with sulfur, the supply and demand for sulfuric acid do not quite balance, with estimated consumption (7.45 million tons) exceeding supply (7.38 million tons). The small discrepancy is again well within the margin of error acceptable for a study of this type. Surprisingly, the breakdown by end use for acid consumption in the 22 western states is similar to the national breakdown in many respects. Fertilizer production still takes over half the total acid consumed, 50.3% in the west versus 54.5% for the entire country. Phosphoric-acid derived fertilizers take more of the acid nationally

Table F-6

SULFURIC ACID SOURCE DATA
22 Western States
(1,000 short tons of 100% sulfuric acid)
1965

Source	Production	Exports[*]	Imports[*]	Net Available[†]
Elemental sulfur	5,768	175	95	
Smelter gases	687			
Refinery sludge acid	933			
Pyrite	77			
Total	7,465	175	95	7,385

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[*] Exports from and imports to the western United States. It was not possible to identify the type of sulfur used to produce the imported and exported acid.

[†] Net available sulfuric acid represents production, minus exports, plus imports, which should equal consumption if changes in stocks are not significant.

Table F-7

SULFURIC ACID CONSUMPTION
22 Western States
1965

Major End Use	Estimated Consumption 1,000 Tons 100% Sulfuric Acid	Percent
Fertilizers		
Phosphoric-acid derived	1,973	26.5%
Normal superphosphate	650	8.7
Ammonium sulfate	1,067	14.3
Other fertilizers	50	0.7
Subtotal, fertilizers	3,740	50.2%
Petroleum refineries	1,541	20.7
Titanium dioxide	393	5.3
Cleaned steel	120	1.6
Hydrochloric Acid	70	0.9
Hydrogen fluoride	333	4.5
Boric acid	57	0.8
Aluminum sulfate	189	2.5
Surface active agents	67	0.9
Uranium and copper	623	8.4
Other materials	312	4.2
Total	7,445	100.0%

(33.3%) than they do in the west (26.5%). Ammonium sulfate, on the other hand, is more important in the west, taking 14.3% of the total acid consumed compared with 8.8% for the whole United States. One important difference in the consumption pattern is in the use of acid for uranium processing and leaching of copper ores; virtually the entire consumption of acid for these purposes (623,000 tons) occurred in the western 22 states. The only other large difference is in the consumption of acid by refineries. Here again the proportion of acid consumed in the west (20.7%) was greater than that consumed nationally (10.5%).

As might be expected, the state-by-state production of sulfuric acid (see Table F-8) closely follows the pattern of sulfur consumption. Here again the greatest production occurs in Texas (2.5 million tons), California (1.4 million tons), and Louisiana (0.8 million tons). Acid was produced in 18 of the 22 western states.

The consumption of acid, however, is somewhat more widely distributed than acid production with at least 1,000 tons being used in 21 of the 22 states. Even so, nearly 80%, or 5.85 million tons, of the total consumption of 7.45 million tons takes place in the five major sulfuric-acid producing states (Texas, California, Louisiana, Missouri, and Idaho).

The prices of sulfuric acid cover a wide range from around $6 a ton up to around $35 a ton. The lower prices apply primarily to captive operations with large plants that are converting the sulfur dioxide in gaseous waste streams to sulfuric acid. The higher prices are typically spot (noncontract) prices charged by the producer with a small acid plant that burns elemental sulfur.

Table F-8

SULFURIC ACID PRODUCTION, CONSUMPTION, AND APPROXIMATE PRICE, BY WESTERN STATE
(1,000 short tons/year except where noted)
1965

Subregion - State	Production	Exports	Imports	Estimated Consumption*	Price Range† ($/ton)
North West Central					
Minnesota	109	0	0	107	
Iowa	82	12	62	79	
Missouri	522	46	165	641	17-23
North Dakota	0	0	0	0	
South Dakota	0	0	12	12	
Nebraska	0	0	0	21	
Kansas	197	151	44	90	6-22
South West Central					
Arkansas	208	73	20	155	
Louisiana	807	196	149	751	14-20
Oklahoma	170	49	0	121	8-22
Texas Panhandle	99	124	170	2,578	14-20
Central Texas	117				
Texas Gulf	2,286				

Table F-8 (concluded)

SULFURIC ACID PRODUCTION, CONSUMPTION, AND APPROXIMATE PRICE, BY WESTERN STATE

(1,000 short tons/year except where noted)
1965

Subregion - State	Production	Exports	Imports	Estimated Consumption*	Price Range† ($/ton)
Mountain					
Montana	88	67	0	22	6-8
Wyoming	90	12	0	78	20-23
Colorado	74	0	0	69	20-22
New Mexico	105	18	18	104	20-23
Idaho	435	45	67	456	7-20
Utah	297	0	0	292	6-26
Arizona	177	11	7	188	7-35
Nevada	97	0	0	97	
Pacific					
Washington	104	25	52	124	9-27
Oregon	0	0	33	33	
California	1,398	9	0	1,427	

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* Consumption based on use, not availability.

† Approximate 1967 prices, 10% or more above production costs.

Ammonium Sulfate

Of the 1.41 million tons of ammonium sulfate produced in the western region in 1965, about 596,000 tons was shipped from the region as shown below:

Exports from Western Region	1,000 Tons of Ammonium Sulfate
Export to Mexico	32.0
Export overseas	546.4
Shipments to eastern United States	17.8
Total	596.2

At the same time, 193,000 tons was shipped into the region.

Imports Into Western Region	1,000 Tons of Ammonium Sulfate
Imports from Canada	152.5
Shipments from eastern United States	41.0
Total	193.5

The ammonium sulfate available for consumption in the western region in 1965 was 1.01 million tons (net available equals production minus exports plus imports) assuming that stock changes were approximately in balance. Virtually all of this material was used as a fertilizer.

The total production of 1.4 million tons of ammonium sulfate was manufactured in six western states with the greatest production occurring in Texas (56.4% of the total) and California (37.6% of the total) as shown in Table F-9. The remainder was produced in Minnesota, Louisiana, Idaho, and Utah.

Although the amount of ammonium sulfate consumed as a simple fertilizer is reported for each state, the state-by-state disposition of the 1.01 million tons of available ammonium sulfate is very difficult to determine because about 35% of the total is used to compound mixed fertilizers. No statistics are available on the exact amount used for this

Table F-9

AMMONIUM SULFATE PRODUCTION AND CONSUMPTION BY WESTERN STATE

(1,000 short tons/yr)
1965

Subregion--State	Production	Exports*	Imports*	Estimated Consumption
North West Central				
Minnesota	1	0	5	6
Iowa	0	0	2	2
Missouri	0	0	6	6
North Dakota	0	0	†	†
South Dakota	0	0	4	4
Nebraska	0	0	8	8
Kansas	0	0	3	3
South West Central				
Arkansas	0	0	2	2
Louisiana	42	59	41	24
Oklahoma	0	0	15	15
Texas	797	522	32	307
Mountain				
Montana	0	0	2	2
Wyoming	0	0	2	2
Colorado	0	0	20	20
New Mexico	0	0	10	10
Idaho	27	0	31	58
Utah	15	3	0	12
Arizona	0	0	19	19
Nevada	0	0	2	2
Pacific				
Washington	0	0	55	55
Oregon	0	0	100	100
California	531	191	0	340

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* Includes shipments to or from other western states.
† Imports and consumption are apparently less than 1,000 tons/yr.

purpose in each state. Furthermore, there are no records to indicate subsequent shipments of mixed fertilizers that contain ammonium sulfate from one state to another. However, SRI has estimated the amounts of ammonium sulfate used both as a simple and in mixed fertilizers in each western state in 1965 and these estimates are shown in Table F-9. According to these estimates, all but about 13,000 tons of the available ammonium sulfate was consumed as fertilizer in 21 of the 22 western states. The greatest consumption, 340,000 tons, took place in California followed closely by consumption in Texas, 307,000 tons. Large quantities were also used in Oregon, 100,000 tons, Idaho, 58,000 tons, and Washington, 55,000 tons. Over 60 percent of the available ammonium sulfate was used in these five states.

Information on the price of ammonium sulfate in each state was not collected. However, price information was obtained for those states where smelter-produced ammonium sulfate might be sold. These data will be presented in the section on Markets for Sulfur By-Products from Smelters.

Sulfur Dioxide

The production and consumption of liquid sulfur dioxide in the western region (about 17,000 tons in 1965) is so small that even if sulfur dioxide produced at smelters could capture the entire market, not enough could be sold to reduce emissions from the smelters in the region to any extent. Therefore, no further information will be collected or presented on the current supply, demand, or price of sulfur dioxide in the western states. Emission problems in localities surrounding a specific smelter might be solved by the production and sale of liquid sulfur dioxide. However, unless large and entirely new markets for sulfur dioxide can be identified in areas where additional markets must be found for smelter by-products containing sulfur, the lack of market and impossibility of widespread use should eliminate the need to consider those parts of recovery processes that would only make sulfur dioxide for sale.

APPENDIX F-4
EXISTING MARKETS FOR SULFUR BY-PRODUCTS FROM SMELTERS

The determination of the potential western U.S. market for smelter by-products requires not only data on markets already provided, but also information on:

- The amounts of each by-product available from each smelter (or group of nearby smelters that could be treated as a marketing entity)
- The feasibility of supplying the smelter by-product to specific markets.

The following tabulation summarizes the data on the markets for sulfur, sulfuric acid, and ammonium sulfate in the western region and the potential production from smelters.

	Western Region	
	Estimated Consumption	Potential Production from Smelters
Sulfur (1,000 long tons)	2,633	1,671*
Sulfuric acid (1,000 tons)	7,445	7,324
Ammonium sulfate (1,000 tons)	997	960†

The data indicate that, if the sulfur products from western smelters could capture essentially all of the estimated markets, it would be possible to sell the entire potential production of sulfur in some form.

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* Excludes sulfur already being recovered as sulfuric acid from smelters.

† Production of ammonium sulfate from only gas streams that contain low concentrations of sulfur dioxide (e.g., stack gases from reverberatory furnaces). The reasons for considering the use of only these dilute streams is explained in the section on ammonium sulfate.

However, if additional supplies nearly equal to the existing markets were made available, as they would be in the case of sulfuric acid and ammonium sulfate, the present suppliers would probably try to match any prices offered by the smelter operators. Such a competitive situation would make it impossible to estimate either the size of the market for the smelter by-products or the price required to sell them. Therefore, the objective in this study and presentation has been to estimate the quantity of each potential smelter by-product that might be sold in an orderly fashion without creating unrestrained price cutting or an excessive hardship on the present suppliers.

An orderly entry of the smelter by-products into the existing market requires that two portions or segments of that market be recognized as unavailable. The first is composed of the markets held by suppliers who are obliged to continue to produce and sell even when the price is so low that no one can make a profit. Examples of such suppliers of sulfur are smelters that make acid, other acid producers that burn sludge acid (primarily from refineries) to recover the sulfur values as regenerated sulfuric acid, and sulfur producers that use their sulfur in captive operations. The unavailable sulfuric acid markets also include those sulfur producers that make their own sulfuric acid and the acid markets that use acid regenerated from refinery sludges. Markets that use by-product ammonium sulfate are also considered unavailable.

The second portion of the unavailable market is located at such distances from the smelter that the cost to transport the product could well exceed the competitive price for the product in the market. Present suppliers of these markets would be difficult if not impossible to displace.

The following tabulation outlines those markets for sulfur, sulfuric acid, and ammonium sulfate that are considered available.

Available Markets

	Sulfur	Sulfuric Acid	Ammonium Sulfate
Markets held by existing suppliers who can probably be displaced	All markets held by producers who do not use their sulfur in captive operations	All markets for acid made from purchased sulfur	Markets for 75% of the ammonium sulfate produced from virgin sulfuric acid
Markets that are within economic shipping distance	All	Those markets where transportation costs do not exceed the delivered selling price	Those markets where transportation costs plus the cost of the ammonia in the product do not exceed the delivered selling price

The size of the available markets for the smelter by-products will represent the greatest amount the smelter operators might reasonably expect to sell, even if they sell at a loss. The smelter operators would obviously prefer to make a profit on the sale of their by-products or at least break even. Therefore, the size of the market which might allow the operators to break even (i.e., production cost equals sales price) has also been determined. This market is henceforth designated as the justifiable market for smelter by-products. The production costs of each smelter operator could not possibly be estimated for each of the processes considered during this project in order to arrive at the breakeven costs for each operator. Instead, the estimated lowest production cost among the producers was selected as the lowest price that the smelter operators would accept for their by-product. The prices used to estimate the sizes of the justifiable markets are as follows:

	$/Ton*	Via
Sulfur	$45	Asarco Process
Sulfuric acid	4	Contact Process
Ammonium sulfate	25	Cominco Process

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* Dollar per long ton for sulfur, dollar per short ton for the other two materials.

Information on transportation costs is essential in order to determine the feasibility of marketing the smelter products. In most instances, freight rates have not been established for shipment of the by-products from the smelters to the potential markets; therefore, these transportation costs must be estimated. Figure 1 shows the plots of transportation costs as a function of distance that were used in this study to estimate the cost to transport elemental sulfur, sulfuric acid, and ammonium sulfate from the smelter to the market by rail. These curves represent estimates based on actual costs of shipping these same or similar products comparable distances between origin and destination in other parts of the country. Obviously existing shipping practices have affected the shapes of the curves on Figure 1. For example, almost no information is available on the cost of shipping sulfuric acid over about 500 miles. We have assumed, therefore, that the shipping cost per ton mile will remain constant beyond 600 miles. Since actual transportation costs must be negotiated, it is conceivable that more favorable rates could be obtained for the very long distance hauls and that the actual costs might fall below the curve on Figure 1 for shipments of over 500 miles.

The curve representing shipping costs for ammonium sulfate may also require some adjustment. The curve represents an estimate based on the cost of shipping bulk agricultural products and on the cost of shipping ammonium sulfate on a few selected routes. However, the curve provided is deemed sufficiently accurate for purposes of this study. The curve of shipping costs for elemental sulfur is considered reliable and fairly accurate, because the data are more abundant and cover a greater range of distances. Even here, however, special rates might be obtained that could result in shipping costs that vary as much as 20% from those estimated from the curve on Figure 1. With this explanation as background, we can now consider the markets for the individual smelter products.

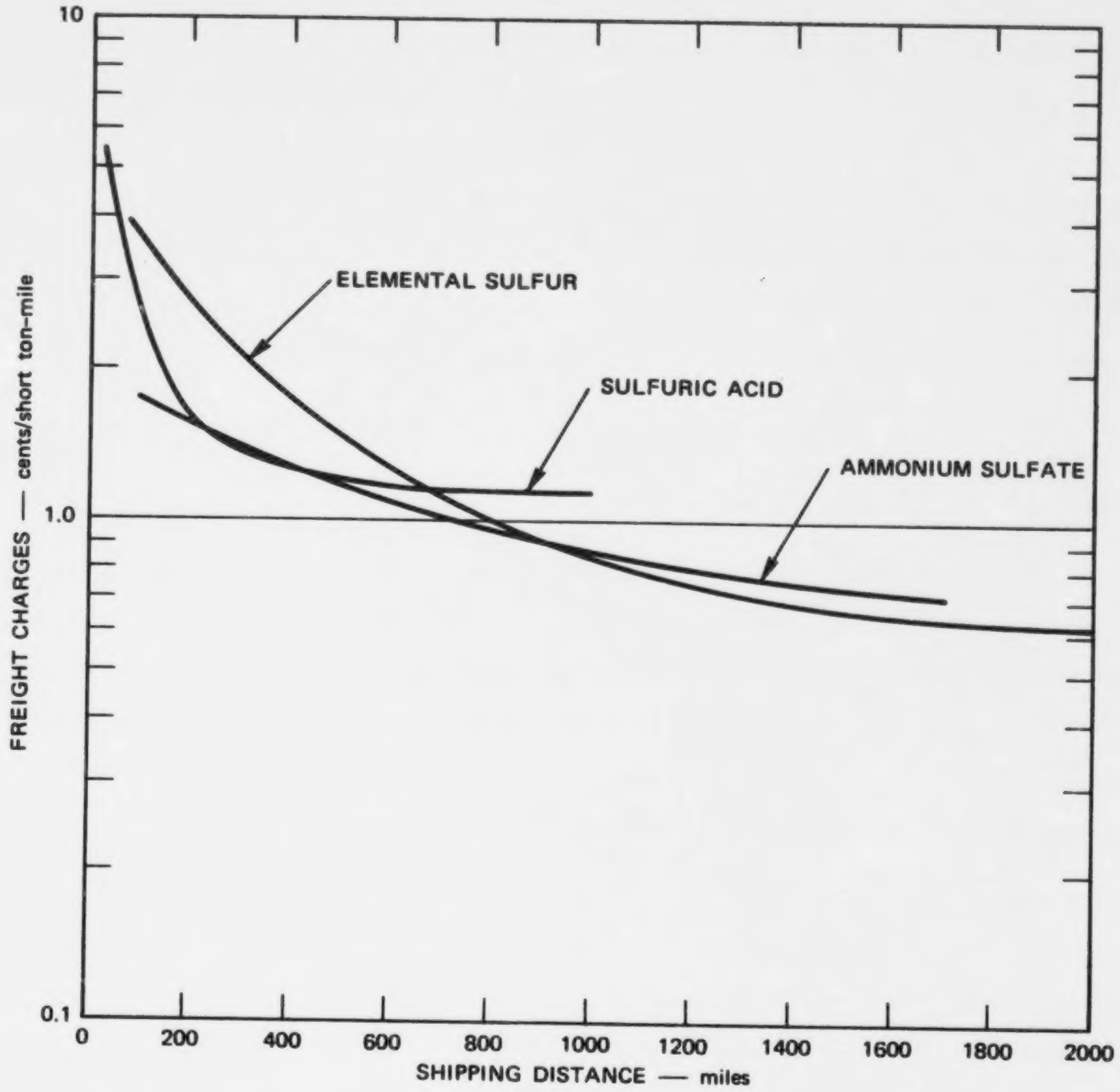

FIGURE 1 SHIPPING COSTS (Sulfur, Sulfuric Acid, Ammonium Sulfate)

Sulfur from Smelters

Available Markets

In addition to the large market for elemental sulfur in the western region, considerable quantities of sulfur could move into the large export market. Table F-10 summarizes the 1965 waterborne export markets for elemental sulfur that are supplied from the United States, Canada, and Mexico. Of the total export of 4.8 million long tons, the Pacific Basin countries receive 1.1 million tons. Many of the western smelters are as close or closer to ports on the Pacific Coast than any of the other major producers of sulfur. Therefore, the Pacific Basin countries should provide better export markets for smelter-produced sulfur than European or South American countries that are supplied sulfur primarily from Gulf Coast ports.

Table F-11 is a compilation of the major available markets for smelter-produced sulfur and of the potential production of elemental sulfur from the smelters by groups. The available market, 6.1 million long tons, is much larger than the 1.67 million long tons of elemental sulfur that might be produced by all the western smelters. Considering the large amounts of elemental sulfur that are shipped long distances throughout the world, displacing the existing suppliers of 1.67 million long tons from their market should not create a chaotic marketing situation for any extended period of time.

Since the available market for smelter sulfur is so large, the major problem is not to determine how much would be sold but rather to determine the markets to which the smelters should sell their sulfur in order to realize the best possible price. Table F-12 is a summation of the data used to identify the markets.

Each smelter and each market within a feasible shipping distance was considered separately in collecting the information. (The groupings of smelters and markets are used in Table F-12 to avoid, where feasible, specific identification of individual smelters or consumers.) For example, the export market best served from Pacific Coast ports could be

Table F-10

WATERBORNE EXPORT MARKETS FOR SULFUR FROM U.S., CANADA, AND MEXICO (1965)

(1000 long tons)

	United States	Canada*	Mexico	Total
Exports to:				
Pacific Basin Countries				
Chile	14.6		--	14.6
Colombia	0.7		3.0	3.7
Ecuador	0.1		--	0.1
Peru	12.1		--	12.1
India	274.9	37.7	--	312.6
S. Korea	9.8		--	9.8
Malaysia	1.0	2.3	--	3.3
Philippines	0.5	13.9	--	14.4
Taiwan	48.7	65.5	11.6	125.8
Japan		28.4		28.4
Australia	140.5	180.7	112.3	433.5
New Zealand	101.6	30.1	28.5	160.2
Subtotal	604.5	358.6	155.4	1,118.5
An Exporting Country			848.3 (to U.S.)	848.3
All Other Countries	2,019.6	308.9	527.6	2,856.1
Total Exports	2,624.1	667.5	1,531.3	4,822.9

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* From Vancouver B.C. only.

Source: U.S. Bureau of Mines.

Table F-11

SMELTER-PRODUCED ELEMENTAL SULFUR
AVAILABLE MARKETS AND POTENTIAL PRODUCTION (WESTERN REGION)
1965

Available Markets for Elemental Sulfur	
Marketing Area	Market Size (1,000 long tons)
Export via Gulf Coast	3,705
Export via Pacific Coast	1,118
Missouri, Kansas, and Iowa	232
California	209
Louisiana	200
Texas	153
Oregon and Washington	142
Idaho and Montana	121
Arizona and New Mexico	68
Oklahoma and Arkansas	61
Colorado and Wyoming	39
Utah and Nevada	37
All other Western States	12
Total	6,097

Potential Production from Smelters (by Group)		
Smelters		Potential Production (1,000 long tons)
Groups	Locations	
Group I-B (7 smelters)	Arizona	603
Group I-A (3 smelters)	Arizona, New Mexico, Texas	374
Group III (4 smelters)	Idaho and Montana	316
Group II (3 smelters)	Utah and Nevada	205
Group V (5 smelters)	Kansas, Missouri, Oklahoma	62
Group IV (2 smelters)	Texas	60
Groups VI, VII (2 smelters)	Pacific Coast	51
Total		1,671

Table F-12

PRICE AND COST DATA RELATED TO MARKETING OF SMELTER-PRODUCED ELEMENTAL SULFUR
(In the Western Region and in the Export Market)

Marketing Area	Competitive Sulfur Price in Marketing Area ($/long ton)	Smelter (by Group) that Can Sell Sulfur in Area	Transportation Cost to Market from Smelter ($/long ton)	Competitive Selling Price at Smelter ($/long ton)
Exports via Gulf Coast	$30	Group IV	$ 7.50-$ 8.50[*]	$21.50-$22.50
		Group I-A	8.00- 9.00[*]	21.00- 22.00
		Group I-B	9.50- 10.50[*]	19.50- 20.50
Exports via Pacific Coast	36	Group I-A	10.00- 10.50[*]	25.50- 26.00
		Group I-B	9.00- 10.50[*]	25.50- 27.00
		Groups II, III	10.00- 10.50[*]	25.50- 26.00
		Groups VI, VII	1.50	34.50
Missouri, Kansas, and Iowa	37-39	Group IV	3.50- †	† - 33.50
California	36-41	Group I-B	9.00- 10.50	29.50- 32.00
		Group II	8.50- 9.00	31.00- 32.00
		Group VII	3.00- 5.00	33.00- 36.00
Louisiana	30	Group V	‡	‡
Texas	30	Group IV	3.50- 8.00	22.00- 26.50
		Group I-A	7.00- 8.50	21.50- 23.00
Oregon and Washington	35-37	Group III	6.00- 11.00	24.00- 31.00
		Group VI	2.00- 8.00	29.00- 35.00
Idaho and Montana	33-35	Group III	8.00- 8.50	25.00- 27.00
Arizona and New Mexico	32-44	Group I-A	6.50- 8.00	25.50- 31.00
		Group I-B	6.00- 8.50	29.50- 34.00
		Group IV	7.00- 7.50	31.00- 31.50
Oklahoma and Arkansas	31-35	Group V	5.00- 7.00	24.00- 26.00
Colorado and Wyoming	30-41	Group II	7.50- 9.50	20.50- 33.50
		Group III	8.00- 9.00	21.00- 22.00
Utah and Nevada	39-40	Group II	6.00- 7.50	31.50- 34.00

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[*] These transportation costs include sales and transshipment charges of $1.50/long ton.

† Higher transportation costs (and lower selling price, f.o.b. smelter) would be incurred between the market and the smelter in the group that is farthest away. This cost was not calculated because the marketing area could be better served from the closer smelters.

‡ Not determined because adequate markets exist in other areas where a higher price could be received for smelter-produced sulfur.

supplied with sulfur from the smelters in Group I (through Los Angeles, California), Group II (through Sacramento, California), and Group III (through Everett, Washington). The smelters in Groups VI and VII could also supply this export market from nearby ports, although they have better markets for any elemental sulfur they might produce. Any of the above smelters supplying this export market could expect to receive $36 per long ton for their sulfur, f.o.b. Pacific Coast port when the world price for sulfur is $30 per long ton, Gulf Coast.

The cost of delivering the sulfur from the smelter and loading it on ships ranges from $9 to $10.50 per long ton for all the smelters in Groups I, II, and III. This cost includes the charges for transshipment from rail car to the boat and the cost of an overseas sales organization. The plant gate price that each smelter might expect to receive for its sulfur is the difference between the price in the market area and the transportation costs. In this example, the plant gate or competitive price the Groups I, II, and III smelters might receive for sulfur sold for export ranges between $25.50 and $27.00 per long ton.

The data summarized on Table F-12 for each smelter and market combination are then combined with the data on the quantities of sulfur available from each smelter and consumable by each market to determine the combination of smelter and market that would allow the smelter operator to receive the highest competitive price for his sulfur.

The markets that could absorb the entire potential production of sulfur from the smelter groups are shown in Table F-13, along with the range of prices the smelter operator might expect to receive for his product when the price of elemental sulfur on the Gulf Coast is $30/long ton. As the data in Table F-13 indicate, markets exist at least theoretically for all of 1.67 million long tons of sulfur the western smelters might produce if the smelter operators sell their sulfur for $25.50 to $35.00 a long ton f.o.b. the smelter.

The sale of the entire production of smelter-produced sulfur at the highest prices requires that over half, 960,000 long tons, be exported.

Table F-13

AVAILABLE MARKETS FOR SMELTER-PRODUCED ELEMENTAL SULFUR*

(1,000 Long Tons)

1965

Marketing Area	Smelter Group							Total
	I-A	I-B	II	III	IV	V	VI-VII	
Export Pacific Coast	336	512		112				960
Missouri, Kansas, and Iowa					36	33		69
California		60	139				10	209
Texas					24			24
Oregon and Washington				100			42	142
Idaho and Montana			16	104				120
Arizona and New Mexico	38	30						68
Oklahoma and Arkansas						29		29
Colorado and Wyoming			13					13
Utah and Nevada	—	—	37	—	—	—	—	37
Total	374	602	205	316	60	62	52	1,671
Selling Prices f.o.b. Smelter ($/long ton)	$25.50- $31.00	$26.00- $34.00	$29.00- $34.00	$26.00- $35.00	$26.50- $31.50	$26.00- $31.00	$35.00	

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* That would provide the greatest return to the smelter operators.

If this tonnage went entirely to Pacific Basin countries, western smelters would be supplying nearly 90% of the 1.1 million long tons of sulfur exported to these countries. It could be argued that the current suppliers of sulfur to this market would not permit another supplier to capture such a high proportion of the market. However, the world demand for sulfur is increasing at the rate of approximately 1.5 million tons/yr. With markets increasing that fast, the U.S. and Mexican exporters could and probably would soon shift their supplies into regions where sulfur is in shorter supply. The combined U.S. and Mexican exports to the Pacific Basin were 760,000 tons in 1965 so at least that much smelter-produced sulfur should be exportable to the region, although it might take 5-10 years to displace entirely the present U.S. and Mexican suppliers.

However, Canadian sulfur would represent the major competition to any exported smelter sulfur seeking to capture the Pacific Basin market as this is also one of their best markets. Just how aggressively the Canadian exporters would defend their position in the Pacific Basin market is impossible to surmise at this time.

Western smelters would not be limited to exporting to just the Pacific Basin countries. The following export statistics from Table F-8 show that nearly half the exports of Canadian sulfur that passed through Vancouver, B.C., went to countries that are not part of the Pacific Basin.

To	Canadian Sulfur Exports (1,000 long tons)
Pacific Basin countries	359
All other countries	309
Total	668

If nearly half of the Canadian sulfur exported through Vancouver can be sold in foreign countries that are located outside the Pacific Basin, then sulfur exported from western smelters that is not sold to Pacific Basin countries might also find markets in other parts of the world. Obviously, they would face more competition in these other markets.

Finally, the price that western smelter operators can receive for their sulfur will vary with the world price -- exemplified by the price on the Gulf Coast. To market all of their potential production, these smelters must sell their sulfur for $4.50/long ton less than the Gulf Coast price. The lower price is the result of transportation cost differentials. However, some of the western smelters could sell all of their production at prices equal to the f.o.b. Gulf Coast prices, and others could charge as much as $5.00/long ton more than Gulf Coast prices for part of their sulfur and still capture small markets. If the price of Gulf Coast sulfur is $30.00/long ton, the smelters should be able to sell all the sulfur they can produce for $25.50/long ton or more. Only if it becomes necessary to sell large quantities of sulfur to markets in countries not bordering the Pacific Basin is the price of smelter sulfur apt to be forced below $25.50/long ton when the Gulf Coast price is $30/long ton.

Justifiable Markets

Since the highest price the western smelters might expect to receive for their sulfur is $35.00/long ton, no sulfur produced by the Asarco process at $45/ton could be sold at or below breakeven costs, so no justifiable market exists.

Sulfuric Acid from Smelters

The size of the markets for sulfuric acid from the western smelters can be estimated from the amount of acid marketed in the area where the smelter acid could be sold competitively. Whether or not the smelter acid can be sold below existing prices depends on the cost of the acid at the smelter, the cost of transporting this acid to the marketing area, and the selling price of the acid already available in the area. Table F-14 contains the data used to determine which marketing areas could be supplied with smelter acid and the prices the smelters might expect to receive.

Table F-14

PRICE AND COST DATA RELATED TO MARKETING
OF SMELTER-PRODUCED SULFURIC ACID (WESTERN REGION)

Marketing Area	Competitive Sulfuric Acid Price in Marketing Area ($/ton)[*]	Smelter (by Group) that can sell Acid in Area	Transportation Cost[†] to Market from Smelters ($/ton)	Competitive Selling Price at Smelter ($/ton)
Louisiana	$10 - $12	Group IV	$8 - 10	$1 - 2
		Group V	7 - 10	1 - 3
Missouri, Kansas and Iowa	15 - 28[‡]			
		Group IV	6 - 9	8 - 10
		Group V	1 - 8	10 - 22
California	13 - 15[‡]			
		Group I-B	8 - 10	4 - 6
		Group II	9 - 12	4 - 6
		Group VII	- [§]	- [§]
Idaho and Montana	10 - 13[‡]			
		Group II	4 - 6	5 - 7
		Group III	0 - 7	6 - 13
Utah and Nevada	14 - 28[‡]			
		Group II	0 - 7	7 - 24
Texas Gulf Coast	8 - 12			
		Group I-A	10 - 11	0 - 2
		Group IV	8 - 9	0 - 3
West Texas and New Mexico	14 - 22			
		Group I-A	0 - 8	10 - 22
		Group IV	0 - 6	10 - 17
		Group V	5 - -	10 - 17

Table F-14 (concluded)

Marketing Area	Competitive Sulfuric Acid Price in Marketing Area ($/ton)[*]	Smelter (by Group) that can sell Acid in Area	Transportation Cost[†] to Market from Smelters ($/ton)	Competitive Selling Price at Smelter ($/ton)
Arizona	$20 - $23			
		Group I-A	$5 - $15	$15 - $19
		Group I-B	0 - 6	17 - 23
Colorado and	14 - 20			
Wyoming		Group II	7 - 13	5 - 17
		Group III	6 - 15	7 - 9
Oklahoma and	10 - 13[‡]			
Arkansas		Group V	1 - 6	5 - 8
Oregon and	17 - 26[‡]			
Washington		Group III	4 - 8	10 - 14
		Group VI	0 - 4	13 - 23

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[*] Competitive prices are calculated assuming that the sulfur required to make the acid costs $30/long ton f.o.b. Gulf Coast.

[†] Cost to transport 93% acid converted to $/ton of 100% acid.

[‡] Smelters in marketing area produce acid for captive use. The price of this acid to the smelter company will be determined arbitrarily to suit the company's accounting procedures. This price may be higher or lower than the indicated competitive price in the area.

[§] Selling price and transportation costs were not determined for this market area-smelter combination.

The selling price of sulfuric acid from the existing sources for each of the marketing areas was used as the basis for determining the price for which the smelter-produced acid might sell in the area, i.e., the competitive sulfuric acid price as shown in Table F-14. For example, if the marketing area is presently supplied with merchant acid, the competitive price listed in the second column of Table F-14 is the same as the determined market price. If the marketing area is supplied from a captive source of acid, the competitive price in the area was assumed to be $2.00/ton less than the cost of producing that acid. Whether merchant or captive, the current acid selling price was adjusted to reflect a reduction in the cost of sulfur in the market area that would correspond to a reduction from the current Gulf Coast price of $39 to $42/long ton to $30/long ton.

The smelter groups that could supply acid to a market and the estimated cost of transporting the acid from the smelter to that market are shown in Table F-14 for each market-smelter combination where the transportation cost does not exceed the competitive selling price in the marketing area. The price, f.o.b. smelter, of acid that would allow the smelters to compete for the acid market in the area is the difference between the competitive selling price in the marketing area and the transportation cost and is shown in the last column on Table F-14. To summarize briefly, the competitive prices in the marketing areas range from $8 to $28/ton, transportation costs from zero to $15/ton, and competitive selling prices at the smelters from zero to $24/ton. The California and West Texas-New Mexico marketing areas are the only ones that could be supplied acid from three smelter groups. The remaining marketing areas could each be supplied from only one or two smelter groups.

Available Markets

The sizes and locations of the markets in the western region that could be supplied with smelter-produced sulfuric acid are summarized in Table F-15. In 1965, the sum of these markets was about 4.4 million tons of sulfuric acid out of a total western market of 7.4 million tons.

Table F-15

SMELTER-PRODUCED SULFURIC ACID MARKETS AND POTENTIAL PRODUCTION (WESTERN REGION) 1965

Markets for Sulfuric Acid

Marketing Area	Market Size (1,000 tons acid)
Louisiana	865
Missouri, Kansas, and Iowa	794
California	692
Idaho and Montana	479
Utah and Nevada	417
Texas Gulf Coast	350
West Texas and New Mexico	221
Arizona	183
Colorado and Wyoming	152
Oklahoma and Arkansas	121
Oregon and Washington	107
Total	4,381

Potential Production from Smelters

Smelter		Potential Production (1,000 tons acid)
Groups	Locations	
Group I-B (7 smelters)	Arizona	2,332
Group I-A (3 smelters)	Arizona, New Mexico, Texas	1,457
Group III (4 smelters)	Idaho and Montana	1,405
Group II (3 smelters)	Utah and Nevada	1,198
Group V (5 smelters)	Kansas, Missouri, Oklahoma	492
Group IV (2 smelters)	Texas	206
Groups VI and VII (2 smelters)	Pacific Coast	234
Total		7,324

The potential production of acid from the western smelters by groups is also given in Table F-15. To achieve the indicated potential production (7.3 million tons/yr) the smelters would convert all of the sulfur oxides currently being emitted in the waste gases in addition to the sulfur oxides now being converted to acid. Approximately 60% of the total potential production of smelter-produced acid could have been sold in 1965 if the entire available market could have been supplied with acid from the western smelters. (The small amount of liquid sulfur dioxide currently recovered is assumed to be produced as it is now. It would not be converted to acid.)

The fact that a market is available does not mean that all or even part of the market could be supplied with smelter acid. The smelters that could supply the market may not produce enough to meet the acid requirements in the area. If all of the available markets for acid are eliminated that are greater than the amounts of acid available from the smelters that could serve the marketing area, the total amount of acid that could be sold to the available markets would be about 3.2 million tons.

Justifiable Markets

Using the data developed for Tables F-14 and F-15, it is possible to determine which smelters could best supply each marketing area, to estimate the quantity of acid that could be supplied, and the f.o.b. selling price for that smelter-produced acid. The results of such a determination are shown on Table F-16. Approximately 2.8 million tons of smelter-produced acid could have been sold to those justifiable markets that existed in 1965 at prices of $4 to $26/ton f.o.b. at the smelter.

The total justifiable market is about 1.5 million tons less than the total available market indicated earlier. Of this 1.5 million tons, 350,000 tons is available market on the Texas Gulf Coast, which cannot be served unless the smelter acid is priced at $0 to $3/ton f.o.b. smelter. Another 328,000 tons of available market in Kansas, Missouri, and Iowa and 865,000 tons in Louisiana are available to the smelters in Groups IV and V, which are within shipping distance of the areas, but all the existing supply

Table F-16

JUSTIFIABLE MARKETS FOR SMELTER-PRODUCED SULFURIC ACID*
(1,000 Tons, 100% Acid)
1965

Marketing Area	Smelter Group I-A	I-B	II	III	IV	V	VI	VII	Total
Louisiana									0
Missouri, Kansas, and Iowa					7	456			463
California		280	332					47	659
Idaho and Montana			337	142					479
Utah and Nevada			417						4[illegible]
Texas Gulf Coast									0
West Texas and New Mexico	108				108	5			221
Arizona	37	146							183
Colorado and Wyoming			112	40					152
Oklahoma and Arkansas					90	31			121
Oregon and Washington				45			62		107
Total	145	426	1,198	227	205	492	62	47	2,802
Selling prices f.o.b. smelter ($/ton)	$10-$22	$4-$23	$4-$24	$6-$14	$8-$17	$5-$22	$13-$23	$18-$26	

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* Based on available markets where the selling price of the acid is $4/ton or more, f.o.b. smelter.

of acid from these smelters is sold to markets where a higher price can be obtained. The remaining 17,000 tons of available but unsupplied market for acid is in the Oklahoma-Arkansas marketing area where, again, the supply of smelter acid from smelters in Groups IV and V is insufficient to meet the demand.

The disposition of acid to the justifiable markets by smelter groups is recapitulated in the following tabulation.

	Sulfuric Acid (1,000 tons)		
Smelter Group	Potential Production from Smelters in Group	Justifiable Market at $4 or More per Ton	Market as a Percentage of Potential Production
I-A	1,457	145	10%
1-B	2,332	426	18
II	1,198	1,198	100
III	1,405	227	16
IV	206	205	100
V	492	492	100
VI VII	234	109	47
Total	7,324	2,802	38%

This tabulation shows that the smelters in Groups II, IV, and V could sell nearly all of the sulfuric acid they might produce for $4/ton or more. The Groups VI and VII smelters might sell nearly half of their potential production. These smelters, however, might expect to receive from $13 to $26 per ton for this acid.

However, Groups I-A and I-B and Group III smelters could only sell 798,000 tons, or about 15% of their potential production of 5.2 million tons. Furthermore, the only added market that might be available to any of the smelters in the latter three groups is along the Texas Gulf Coast, and then only if they charged nothing (f.o.b. smelter) for their acid. Even if they could supply the entire available market in that marketing area, the three groups could still sell only about 22% of their combined potential production.

This Texas Gulf Coast market is also the only additional market that could be supplied with smelter acid, even if the price of Gulf Coast sulfur was higher than the $30/long ton assumed in calculating the selling price of acid made from elemental sulfur. If this Gulf Coast market could be supplied, the justifiable markets for smelter-produced acid would be increased from 2.80 to 3.15 million tons or 13%. However, based on some approximate calculations, it appears that the price of sulfur would need to be $50/ton before all of this market would use smelter-produced acid. This 67% increase in price of sulfur from $30 to $50/ton required to increase the market by 13% indicates how inelastic the markets are for smelter acid.

Ammonium Sulfate from Smelters

Ammonium sulfate is the remaining possible sulfur by-product for which large markets might exist. Ammonium sulfate is used primarily as a fertilizer that provides necessary nitrogen to the soil. While the sulfate portion of the ammonium sulfate is rarely considered in pricing, it also plays a vital role in improving the crop yields from many soils that are deficient in sulfur. The major agricultural areas in this country with a sulfur deficiency are in West Texas and west of the Rocky Mountains. Western smelters should be well situated to serve these areas.

The total market for ammonium sulfate in the western region was almost 1 million tons in 1965. The western smelters could make about 10 million tons/yr if all of their sulfur dioxide was recovered as ammonium sulfate. Thus, the very most these smelters could expect to market would only be 10% of their total potential production.

Therefore, the smelter production of ammonium sulfate from the processing of dilute streams (waste gases from copper reverberatory furnaces and zinc sintering machines) was assumed to be sufficient. Utilization of these streams would provide 924,000 tons, probably more ammonium sulfate than could be sold. Furthermore, production of ammonium sulfate is the only method in use today to control the emissions from these dilute streams.

The method used to estimate the markets for ammonium sulfate differs somewhat from the method used to estimate the market for the other by-products in that the potential sales of ammonium sulfate are assumed to be no more than 75% of the available market rather than the 100% assumed for sulfur and sulfuric acid.

The reason for selecting 75% as the maximum level of sales to the available market is that a low price for ammonium sulfate produced by smelters will not necessarily result in complete displacement of other existing suppliers from the market. Selling ammonium sulfate, the smelters would be competing directly with the existing suppliers who would be forced to meet this competition since alternate markets are not as readily available. Under the circumstances, 75% of the available market appears to be the maximum the smelter operators could expect to capture.

Table F-17 contains the data on prices and transportation costs that were used to determine which marketing areas could be supplied with smelter-produced ammonium sulfate and the prices the smelters might expect to receive. To summarize briefly, the competitive prices in the marketing areas range from $29 to $39 for a ton of ammonium sulfate. Transportation costs vary from nothing to $10/ton for those combinations of smelters and markets where it was apparently feasible to consider the shipment of the ammonium sulfate. What is considered an unfeasible shipment is explained in detail in the footnotes to Table F-17. Briefly, the unfeasible shipments are those to markets that can be supplied completely by smelters that are closer. Based on the above prices at the market and the transportation costs, the competitive selling prices at the smelters would range from $19 to $35/ton.

Available Markets

The available markets for ammonium sulfate, by definition, are those markets that could be achieved if the selling price, f.o.b. smelter, is equal to or higher than the cost of the contained ammonia. (Ammonia would cost the smelter operators from $50 to around $70/ton whether they produced it themselves or had it delivered.) The f.o.b. price of smelter-

Table F-17

PRICE AND COST DATA RELATED TO MARKETING OF SMELTER-PRODUCED AMMONIUM SULFATE (WESTERN REGION)

	Competitive Ammonium Sulfate Price in Marketing Area[*] ($/ton)	Smelters (by Group) That Can Sell in Area	Transportation Cost to Market from Smelters ($/ton)	Competitive Selling Price at Smelter ($/ton)
Texas	$29.00-36.50	Group I-A	$6.50-9.30	$19.70-30.00
		Group I-B	7.50-10.00	19.00-29.00
		Group IV	0.00-7.00	22.00-36.50
		Group V	5.00-7.00	22.00-31.00
California	29.00-32.50	Group I-A	6.50-9.50[†]	20.50-26.00[†]
		Group I-B	3.50-9.00	20.50-29.00
		Group II	8.00-9.50[†]	21.00-23.00[†]
		Group III	2.00-7.00	25.50-29.00
Oregon and Washington	36.00-37.00	Group II	9.00- ...[‡]	... -28.00[‡]
		Group III	6.00-7.50	29.50-31.00
		Group VI	1.50-3.00	34.00-34.50
Idaho and Montana	35.00-38.00	Group II	3.00- ...[‡]	... -35.00[‡]
		Group III	1.50-4.00	33.50-34.00
		Group IV	8.00- ...[‡]	... -30.00[‡]
Arizona and New Mexico	31.00-36.50	Group I-A	4.50-6.50[†]	25.00-32.00[†]
		Group I-B	1.50-3.00	23.00-35.00
		Group IV	2.00- ...[‡]	... -29.00[‡]

Table F-17 (concluded)

	Competitive Ammonium Sulfate Price in Marketing Area[*] ($/ton)	Smelters (by Group) That Can Sell in Area	Transportation Cost to Market from Smelters ($/ton)	Competitive Selling Price at Smelter ($/ton)
Colorado and Wyoming	$39.00	Group I-A	$7.50- ...[‡]	... -31.50[‡]
		Group I-B	8.50- ...[‡]	... -30.50[‡]
		Group II	6.00-6.50[†]	$32.50-33.00[†]
		Group III	7.50- ...[‡]	... -31.50[‡]
		Group IV	5.50- ...[‡]	... -33.50[‡]
Oklahoma and Arkansas	34.50-35.00	Group I-A	7.50- ...[‡]	... -27.50[‡]
		Group IV	4.00- ...[‡]	... -31.00[‡]
		Group V	2.50-6.00	29.50-32.50
Missouri, Kansas, and Nebraska	33.00-38.50	Group IV	4.50- ...[‡]	... -33.50[‡]
		Group V	2.00-5.50	27.50-34.00
Utah and Nevada	33.00	Group II	3.50-4.00	29.00-29.50

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[*] Competitive prices are calculated assuming that ammonium sulfate would be sold for $29/ton f.o.b. large producers.

[†] Higher transportation costs (and lower selling price, f.o.b. smelter) would be incurred between the market and the smelter farthest away. This cost was not calculated because the marketing area could be better served from the closer smelters.

[‡] The higher transportation cost (and the resulting lower selling price at the smelter) was not calculated for this combination of marketing area-smelter group because the marketing area could be better served from closer smelters where transportation costs would be lower than from this smelter group-marketing area combination.

produced ammonium sulfate to sell to the available market, therefore, must equal or exceed \$13-\$18/ton. All of the markets identified in Table F-17 can be considered available since the competitive selling prices at the smelters exceed \$18/ton.

Table F-18 summarizes the data on the sizes and locations of the available markets in the western region for smelter-produced ammonium sulfate. In 1965 the total available market was about 835,000 tons of ammonium sulfate out of a total market of 997,000 tons.

The potential production of ammonium sulfate from the western smelters by groups is also given in Table F-18. To achieve the indicated production (924,000 tons/yr) the smelter operators would use the Cominco process to convert the sulfur oxide currently being emitted in the dilute waste gases (previously defined). Approximately 2.3 tons of ammonium sulfate is produced per short ton of sulfur in the waste gas treated. The remainder of the sulfur oxides from these dilute gas streams would be recovered as concentrated sulfur dioxide, which could be used to increase the concentration of the sulfur dioxide in the gas stream to a sulfuric acid plant.

Under the assumption that sales of smelter-produced ammonium sulfate are 75% of the available market, the smelters could sell about 626,000 tons/yr or 68% of their potential production as defined.

Justifiable Markets

The data developed in preparing Tables F-17 and F-18 can be used to determine the economically justifiable markets for the smelter-produced ammonium sulfate. The results of this determination are shown on Table F-19. Approximately 435,000 tons of smelter-produced ammonium sulfate could have been sold to markets that existed in 1965 at prices of \$25/ton to \$36/ton f.o.b. at the smelter.

The minimum justifiable selling price for the smelter-produced ammonium sulfate was set arbitrarily at \$25/ton. The process economics described earlier in this report indicates that the operating costs might range from \$28 to \$135/ton, depending upon the size of the plant

Table F-18

SMELTER-PRODUCED AMMONIUM SULFATE: MARKETS AND POTENTIAL PRODUCTION
(WESTERN REGION)

Available Markets for Ammonium Sulfate	
Marketing Area	Market Size (1,000 tons)
Texas	307
California	235
Oregon and Washington	155
Idaho and Montana	60
Arizona and New Mexico	29
Colorado and Wyoming	19
Oklahoma and Arkansas	17
Missouri, Kansas, and Nebraska	11
Utah and Nevada	2
Total	835
75% of total	626

Potential Production from Smelters (by Group)		
Smelter		Potential Production (1,000 tons)
Groups	Locations	
Group I-B (7 smelters)	Arizona	349
Group I-A (3 smelters)	Arizona, New Mexico, Texas	224
Group II (3 smelters)	Utah and Nevada	219
Group III (5 smelters)	Idaho and Montana	75
Group IV (2 smelters)	Texas	31
Groups VI and VII (2 smelters)	Pacific Coast	19
Group V (5 smelters)	Kansas, Missouri, Oklahoma	7
	Total	924

Table F–19

JUSTIFIABLE MARKETS FOR SMELTER–PRODUCED AMMONIUM SULFATE (WESTERN REGION)
(1,000 Tons)
1965

Marketing Area	Smelter Group I–A	I–B	II	III	IV	V	VI–VII	Total Justifiable Market*	Justifiable Market as Percent of Total Available Market
Texas	149				31			180	59%
California		40						40	17
Oregon and Washington			24	73			19	116	75
Idaho and Montana			43	2				45	75
Arizona and New Mexico	8	14						22	75
Colorado and Wyoming			14					14	75
Oklahoma and Arkansas	11							11	75
Missouri, Kansas, and Nebraska						7		7	65
Total	168	54	81	75	31	7	19	435	52%
Selling price f.o.b. smelter ($/ton)	$25.00-30.00	$28.50-35.00	$28.00-35.00	$31.00-33.50	$34.00-36.50	$29.50-34.00	$33.00-34.50		

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* Up to 75% of the total available market in each marketing area.

and how the costs are allocated between the ammonium sulfate and the sulfur dioxide coproducts. The largest Cominco process plant considered in the process economic portion of the study would produce 65,000 tons/yr of ammonium sulfate, while three of the smelters could make between 110,000 and 160,000 tons/yr. It is conceivable that ammonium sulfate might be produced at these latter smelters for as little as $25 to $30/ton if the operating costs were divided equally between the two products.

The total justifiable market for ammonium sulfate amounts to 435,000 tons. This is 191,000 tons less than 75% of the available market. About 137,000 tons/yr of this unavailable market is in northern California. The smelter operators would have to sell their ammonium sulfate for about $20.50/ton f.o.b. the smelter in order to capture this market. Another unavailable market of 50,000 tons/yr is in Texas. The smelter operators would have to sell their ammonium sulfate for even less (under $19.00/ton) in order to capture this market.

The disposition of the ammonium sulfate to the justifiable markets by smelter groups is recapitulated in the following tabulation.

Production and Markets for Ammonium Sulfate
by Smelter Group
(1,000 tons)

Smelter Group	Potential Production from Smelter Group	Justifiable Market at $25 or More per Ton	Market as a Percentage of Potential Production
I-A	224	168	75%
I-B	349	54	15
II	219	81	37
III	75	75	100
IV	31	31	100
VI VII	19	19	100
V	7	7	100
Total	924	435	57%

This compilation shows that the smelters in Groups III through VII could sell all of the ammonium sulfate they might produce for $25/ton or more;

while the Group I-A smelters could sell about three-fourths of their total potential production. However, the Groups I-B and II smelters could sell only 15 and 37%, respectively, of their potential production. The western smelters as a whole might sell up to 47% of their combined potential production of ammonium sulfate.

It should be noted that production of 435,000 tons of ammonium sulfate would not increase the amount of sulfur dioxide recovered from smelter emissions by a proportionate amount. For example, the smelters in Groups II, IV, and V have already been shown to have sufficient markets for sulfuric acid available to them to permit them to recover all of their sulfur emissions as the acid. The ammonium sulfate market identified for the smelters in these groups merely provides an alternate way of handling the recovery of their emissions that may or may not be better suited to their particular operation.

Even the smelters in Groups I, III, VI, and VII, which cannot dispose of all the acid they might produce, would not be able to reduce their emissions by production of ammonium sulfate because this ammonium sulfate would only replace that made at other locations by other companies that would have bought smelter acid to make their product. The only exception to this situation arises with the Group I-A smelters selling in the Texas market. In this case the ammonium sulfate would displace ammonium sulfate made primarily along the Gulf Coast using acid produced on the Gulf Coast. The sale of smelter-produced ammonium sulfate to the Texas markets would increase the potential disposal of recovered emissions from the Group I-A smelters by the equivalent of about 70,000 tons of sulfuric acid. This increase in recovered emissions would not appreciably improve the difficult marketing situation faced by these smelters. They could produce the equivalent 1.46 million tons of sulfuric acid if all of their emissions were recovered. The potential market for their acid is only 145,000 tons. Even if they were able to capture all of the potential markets for acid (145,000 tons) and ammonium sulfate (the equivalent of 70,000 tons of acid) they would still need to find markets for the equivalent of 1.24 million tons of acid.

APPENDIX F-5

FUTURE MARKETS FOR SULFUR BY-PRODUCTS FROM SMELTERS

Future markets can be considered in two separate categories. First, the markets that are currently large enough to absorb the potential smelter production of by-products and, second, the markets that are not now capable of absorbing the smelter production but might be in the future. As long as the markets in the first category grow faster than the increase in smelter production, smelters that could have sold all their potential production in 1965 will be able to do so in the future. Only if smelter production increases faster than the markets for by-products can these smelters sell proportionately less of their total future emissions than they might now.

Table F-20 is a recapitulation of the present and future markets for sulfur (and sulfuric acid) by region of the country. According to the estimates shown on Table F-20, markets for sulfur and sulfuric acid in the eastern region will both increase by over 2 million long tons of sulfur (or sulfur equivalent) between 1965 and 1975. Markets for these products in the western region should increase by about 1 million long tons over the same ten-year period.

Changes in the amount of sulfur potentially available from smelters will be related to changes in metal production. Copper, lead, and zinc productions are predicted to grow an average of 3%, 2%, and 2.5%, respectively, each year between now and 1975 (see Section VII for future metal demand). If these growth rates are achieved, and assuming the ratio of metal to sulfur in the concentrate charge to the smelter does not change appreciably, the total sulfur equivalent available from U.S. nonferrous smelters will increase from 2.45 to 2.98 million long tons/yr between 1968 and 1975.

Table F-20

SULFUR MARKETS AND PRODUCTION AT SMELTERS
1965-1975

	Estimated Increases in Markets for Sulfur or Sulfur Equivalent, Million Long Tons/Yr		
	Sulfur Markets		
Markets	1965	1975	Increase in Markets from 1965 to 1975
Eastern Region	5.47	7.75	2.28
As acid	4.66	6.72	2.06
Western Region	2.63	3.72	1.09
As acid	2.24	3.15	0.91
U.S. Total	8.10	11.47	3.37

	Potential Recovery of Sulfur or Sulfur Equivalent, Million Long Tons/Yr		
	Smelter Production		
Smelters	1968	1975	Increase in Production from 1968 to 1975
Eastern Region	0.31*	0.38	0.07
Western Region	2.14*	2.60	0.46
U.S. Total	2.45	2.98	0.53

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* Includes sulfur contained in sulfuric acid now being produced.

Assuming also that the increases in smelter production will be distributed regionally in proportion to current production, only 70,000 long tons/yr more sulfur will be available from the eastern smelters in 1975 than was available in 1968. Since this increased tonnage represents only about 4 percent of the total increase in markets anticipated for the eastern region, it is almost a certainty that the increase could be absorbed.

Increased production from the smelters in the western region could add 460,000 long tons of sulfur or sulfur equivalent; less than half the estimated increase in use of sulfur in the region. Even in the western region, any of the smelters that now have sufficient markets for their entire production will probably be able to market their potential 1975 production.

It has already been shown that all of the western smelters could sell all or nearly all of their potential production of elemental sulfur in existing and presumably future markets. From the standpoint of adequacy of markets, sulfur is definitely the preferred smelter by-product.

However, the known processes for production of elemental sulfur at smelters are apparently uneconomical unless the stack gas concentrations of sulfur dioxide are higher than the present concentrations at most U.S. smelters. Economic recovery of sulfur dioxide emissions from the smelters might be achieved if sulfuric acid or ammonium sulfate can be produced and if future (1975) markets for these products are large enough to absorb the total 1975 potential production.

Existing markets can absorb most of the potential production from all U.S. smelters except for the Group I, III, VI, and VII smelters in the western region. The question of whether the potential production from these smelters could be utilized in the markets that could exist in 1975 is examined in the next sections.

By-Products from Group I Smelters

The 10 Group I smelters in Arizona, New Mexico, and far west Texas can produce as much as 3.8 million tons/yr of sulfuric acid. In 1965 the available market for acid from these smelters was an estimated

570,000 tons, or about 15 percent of the potential production. The equivalent of another 68,000 tons of acid might be sold in the form of ammonium sulfate. Even so, additional markets for nearly 3 million tons of acid, or 4 million tons of ammonium sulfate, or an equivalent combination must be found if the Group I smelters are to dispose of their emissions of sulfur dioxide by recovering them as one or both of these products.

Sulfuric Acid

The potential market for sulfuric acid that existed in 1965 was divided roughly as follows:

Market	Potential Consumption of Sulfuric Acid from Group I Smelters in 1965	
	Tons	Percent
Fertilizer production	285,000	50%
Leaching of copper ores	195,000	34
Uranium ore processing	70,000	12
Other	20,000	4
Total	570,000	100%

The potential for expansion of these existing uses will be considered first.

The 285,000 tons of sulfuric acid that could be used for production of fertilizers would be sold mostly to northern California fertilizer producers to replace sulfuric acid made from Canadian elemental sulfur. Additional sulfuric acid could be sold to these producers in the future in place of any extra Canadian sulfur they might need to increase fertilizer production. The amount of additional smelter-produced acid that might be sold to this market will depend upon:

- The amount of additional sulfuric acid required by these producers
- The amount of extra sulfur (or sulfur equivalent) required in the state beyond what can be supplied from local oil refineries. (The uses for the latter sulfur are considered unavailable.)

The fertilizer producers in California use sulfuric acid to make phosphate fertilizers, ammonium sulfate, and mixed ammonium phosphate-ammonium sulfate fertilizers. Demand for these fertilizer materials has been growing and is expected to continue to grow. As a result, the California fertilizer industry should require 390,000 tons/yr more acid in 1975 than in 1965.

Total annual sulfuric acid demand in California is expected to increase from 1.4 million short tons in 1965 to 2.2 million short tons by 1975 (800,000 tons/yr). At the same time recovery of sulfur from oil refinery streams should increase from 220,000 to 400,000 long tons/yr by 1975, and this additional sulfur will provide 600,000 of the 800,000 short tons/yr of extra sulfuric acid required by 1975. Therefore, no more than 200,000 short tons/yr of additional sulfuric acid must either be produced from imported elemental sulfur (most likely Canadian) or be imported (sulfuric acid from Arizona). (Presumably, part of the additional acid needed for fertilizer production in 1975 will be made from oil refinery sulfur.) Therefore, 200,000 tons/yr is the greatest amount of additional sulfuric acid, from the Group I smelters, that could be consumed in California, most likely for the manufacture of fertilizer.

Some smelter-produced acid could also be used to make fertilizers for the markets in Arizona and New Mexico. These markets, however, will not require more than about 50,000 tons/yr of extra acid by 1975.

Leaching of copper ores constituted the largest market for sulfuric acid in Arizona and New Mexico in 1965. Leaching has already increased markedly since 1965 and shows every indication of continuing to expand. The consumption of acid in the leaching of ores, by areas, within the copper-producing regions for 1965 and 1968, and estimates of the consumption for the 1970-1975 period are summarized in Table F-21. Consumption increased at an average annual rate of 21% between 1965 and 1968, growing from 195,000 to 350,000 tons/yr. By 1975 consumption can easily reach between 800,000 and 975,000 tons/yr (an annual growth rate of 12 to 14%) if acid from the Group I smelters becomes plentiful and if existing plans for use of acid are carried out by the mine operators in the area.

Table F-21

ACID FOR LEACHING OF COPPER ORES

(In Areas that Could be
Supplied with Acid
from
Group I Smelters)

Copper Mining Area	Estimated Sulfuric Acid Consumption (1,000 tons)		
	1965	1968	1970-75
Northern Arizona*	50	75	125-165
Central Arizona†	135	200	525-600
Southern Arizona‡	2	5	25-35
Eastern Arizona - Western New Mexico§	18	70	125-175
Total	195	350	800-975

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* North of Wickenberg.

† Miami, Superior, San Manuel, etc.

‡ Twin Buttes, Ajo, Bisbee, Silver Bell, etc.

§ Safford, Morenci, Santa Rita, Tyrone. Part of this acid is consumed in the leach-precipitation-float circuit employed at Morenci. The acid is used to dissolve soluble copper minerals in the ore so they can react with sulfides to yield a product that can be recovered in the flotation cells.

In addition to the existing deposits that are leached with acid and new deposits that are scheduled to be developed, a number of other known low-grade deposits might be mined that could require acid for leaching.

There are also numerous good-sized deposits of acid-soluble copper minerals of suitable grade bedded in limestone that would consume too much acid to permit economic leaching. Research is being undertaken to find ways to remove the limestone by physical means so that these ores can also be leached. If means were found to effect the separation, additional acid would be consumed in leaching these ores. It is possible that under the most favorable circumstances another 100,000 tons/yr of sulfuric acid might be used in Arizona and New Mexico by 1975 to leach copper from ores. This would result in a maximum consumption of 1.1 million tons/yr of sulfuric acid for leaching in the area by 1975.

The third largest potential market for acid from the Group I smelters is in the processing of uranium ores. After reaching a peak production in 1960, the output of uranium has declined gradually as the requirements of the U.S. Government were fulfilled. Within the past 2 years, however, a number of large nuclear-powered plants for generating electricity have been ordered, so the annual production of uranium (as yellowcake--U_3O_8) is expected to increase.

The Group I smelters are close enough to the uranium mills in New Mexico so that they could supply the acid requirements of these mills. According to estimates of future U_3O_8 production made by the U.S. Atomic Energy Commission, the New Mexico mills could use an additional 150,000 tons/yr of sulfuric acid by 1975.

Markets for smelter-produced sulfuric acid for other than fertilizers, copper leaching, or uranium processing are relatively small in the area that might be supplied with acid from the Group I smelters. Although considerable acid is used for other purposes within shipping range of these smelters in the vicinity of Los Angeles, this market is considered to be unavailable to smelter acid because of the by-product nature of the acid currently sold there. The acid is produced in plants that are either run by or closely linked to the oil refineries in the area. Since the refineries depend upon these plants to accept refinery spent acid for reprocessing and to process their waste hydrogen sulfide, the acid plants are, in effect, part of the refinery and cannot be replaced. These acid plants also supply considerable acid to other, nonrefinery customers. Here again a substantial part of the acid is returned after use to be fortified or reburned. Even the market for single-use acid is not considered penetrable since the refinery-based acid plant can affort to compete for this market on virtually any terms necessary to keep the business. Therefore, no great expansion is foreseen in the "other-uses" market for acid from Group I smelters. This market might at most double from 20,000 to 40,000 tons/yr by 1975.

Finally, it is possible that entirely new markets might develop for acid from the Group I smelters although the liklihood seems small. For example, several large low-grade manganese deposits are known to exist in both Arizona (the Artillery Mountains near Kingman) and in New Mexico (near Silver City). If these deposits were developed, sulfuric acid or possibly sulfur dioxide would be required for the leaching of the manganese values. A more detailed evaluation would be required to determine the quantity of acid that might be used for this purpose. However, indications are that the quantities of acid required would not be great even if these deposits were developed.

A number of ilmenite deposits are also found in the area. One of the larger deposits is near Bagdad, Arizona. However, most of these deposits are low grade and recovery with subsequent processing to manufacture titanium dioxide (which would require sulfuric acid) is not contemplated. To our knowledge, no phosphate deposits of any commercial significance have been found in the area even though exploration programs have been undertaken.

No local phosphate rock is available for treatment with sulfuric acid from the Group I smelters to make phosphate fertilizers.* However, the possibility of using this acid to make phosphates out of rock from Idaho for the Midwest market was examined. The best conceivable Midwest market to be served would:

- Require relatively large amounts of phosphate fertilizer
- Be as far away as possible from Florida, the alternate source of the fertilizers
- Be accessible by rail transport, preferably from both Idaho and from the Group I smelters, since railroad is the feasible means of transport. The distances between the source of raw materials and the market are too great to consider truck transport, and the quantities are too small to make use of pipelines economical.

The farming area in the vicinity of Hutchinson, Kansas, appears to meet the above qualifications as well as or better than any other. Approximately 102,000 tons of P_2O_5 was used in commercial fertilizers in Kansas in 1965.

All possible combinations of plant locations were considered. However, transportation of western (Idaho) phosphate rock and Group I sulfuric acid to the plant near the market would require 3% fewer ton-miles of transportation than either of the two alternative locations per unit of fertilizer delivered, as shown below. This is a small difference and special rate concessions could easily make a Group I smelter or even an Idaho phosphate mine the favored location. In the absence of more specific data we have assumed that the plant in Kansas would result in the lowest overall transportation costs.

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* Phosphorus-containing fertilizers are produced from phosphate rock by several methods. The most common method is by reaction of the rock with acid. Sulfuric acid is ordinarily the most economical acid for this use. Simple reaction of phosphate rock with sulfuric acid results in single superphosphate, a low quality phosphate fertilizer. Higher quality products are produced by extracting phosphoric acid from the reaction mixture and reacting it with additional phosphate rock to produce triple superphosphate or reacting it with ammonia to produce ammonium phosphate. The higher plant food content of these materials makes them most desirable from the standpoint of minimizing the expense of their transport, storage, and application. The phosphorus content of fertilizer materials is customarily expressed in terms of their equivalent contents of P_2O_5.

	Ton-Miles of Transportation* with Fertilizer Plant in the Vicinity of:		
	Phosphate Mine (Idaho)	Group I Smelter	Market (Kansas)
Phosphate rock (3.2 tons/ton P_2O_5)	0	4,445	3,626
Sulfuric acid (2.7 tons/ton P_2O_5	3,750	0	1,958 (min)
Fertilizer, phosphoric acid, (54% P_2O_5, 1.85 tons/ton P_2O_5)	2,096	1,341 (min)	0
Total	5,846	5,786	5,584

A plant in Kansas with a 200 ton/day capacity, operated 340 days a year, would supply 68,000 tons of P_2O_5/yr or two-thirds of P_2O_5 used in Kansas in 1965. Such a plant would be about the largest that would be practicable to build in the area.

Figure 2 illustrates, as a function of the Gulf Coast price for elemental sulfur, the estimated costs of 50% P_2O_5 fertilizer delivered to fertilizer distributors in Hutchinson, Kansas, from:

1. A 200 ton/day plant at Hutchinson using Idaho phosphate rock and sulfuric acid from the Group I smelters.
2. A 600 ton/day plant in Florida using local phosphate rock and sulfuric acid made from Gulf Coast sulfur.

As can be seen from Figure 2, fertilizer from the Hutchinson, Kansas, plant would not be competitive in that market until the price of sulfur on the Gulf Coast reached about $47/long ton. Such a high sulfur price between now and 1975 is most unlikely.

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* **Mileages:**

From	To	Miles
Pocatello	Hutchinson	1,133
Pocatello	Group I smelter	1,389
Group I smelter	Hutchinson	725 (min)

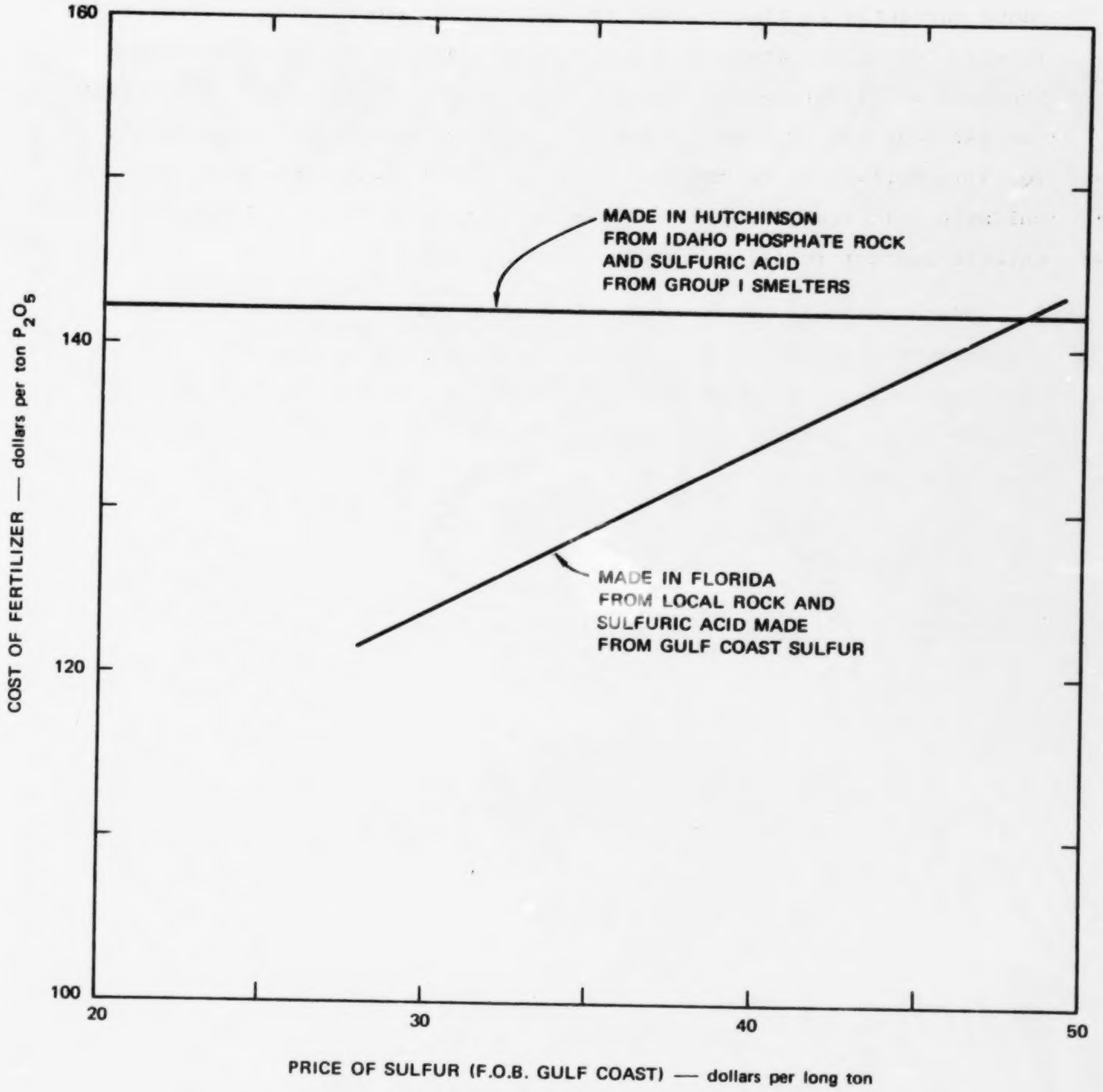

FIGURE 2 RELATIVE COSTS OF 50% P_2O_5 FERTILIZER DELIVERED TO DISTRIBUTOR IN HUTCHINSON, KANSAS
Assuming Existing Freight Rates

The above comparison was based on existing freight rates for sulfuric acid, phosphate rock, and phosphate fertilizer. Even if rates two-thirds those currently in effect could be negotiated, which seems extremely unlikely, fertilizer from the Florida plant would still be cheaper than that produced at Hutchinson as long as the price of sulfur on the Gulf Coast was $42/long ton or less. Hence, it does not appear that a phosphate fertilizer plant in Hutchinson, Kansas, using western phosphate rock and sulfuric acid from Group I smelters could compete for the local fertilizer markets against fertilizer produced in Florida.

Since entirely new markets for sulfuric acid do not seem promising, the increased use of acid from the Group I smelters will result almost exclusively from the expansion of existing markets. These markets should be able to use between 1.5 and 1.9 million tons of acid in 1975 as broken down by markets in Table 22.

Table 22

ESTIMATED MARKETS FOR ACID FROM
GROUP I SMELTERS IN 1975

Market	Acid Required (1,000 tons)
Leaching of copper ores	800-1,100
Fertilizer production	500
Uranium ore processing	220
Other	40
Total	1,560-1,860

Based on these estimates, less than one-half of the total sulfur dioxide currently being emitted or recovered as sulfuric acid by the Group I smelters could be recovered as sulfuric acid and sold for $4/ton or more, f.o.b. the smelter, in 1975.

Ammonium Sulfate

The Group I smelters can recover 570,000 tons/yr of ammonium sulfate by treating the waste streams that contain less than 3% sulfur dioxide. The present justifiable markets and available markets for ammonium sulfate from the Group I are as follows:

Markets for Ammonium Sulfate from Group I Smelters
(1,000 Tons/Yr)

Market Type	Market Area California	Texas and Oklahoma	Arizona and New Mexico	Total
Total Available	177	210	22	409
Justifiable	40	160	22	222
Other available	137	50	0	180

The Group I smelters might sell 409,000 tons/yr of ammonium sulfate or 72% of their potential production if they were willing to charge as little as $19/ton, f.o.b. smelter, for their product and capture 75% of the market available to them. On the other hand, the Group I smelters might sell 222,000 tons/yr of ammonium sulfate or less than 40% of their potential production if they sell only to those existing markets that will return to them $25 or more per ton of product (f.o.b. smelter).

The future sales of ammonium sulfate from Group I smelters whether they sell to just the justifiable markets or to the available markets, will depend on the future use of ammonium sulfate as a fertilizer in the market areas shown in the tabulation above.

The average annual growth rate in consumption of ammonium sulfate to be anticipated between 1965 and 1975 and growth of the available markets are summarized in the following tabulation.

Market	Estimated Annual Growth Rate 1965-1975 (percent)	Additional Available Market in 1975 (1,000 tons/yr
California	4%	112
Arizona and New Mexico	3	10
Texas and Oklahoma	4	148
Total		270

The 270,000 tons of additional available market combined with the current available market (409,000 tons/yr) would be more than large enough to absorb the present potential production from the Group I smelters (573,000 tons/yr). Ammonium sulfate production from the Group I smelters could increase from 573,000 to 679,000 tons/yr by 1975 and still not exceed the total available market for ammonium sulfate in the area.

Such an increase in production would represent a 1.8% average annual increase in production of sulfur dioxide emissions from the reverberatory furnaces in the Group I smelters. Smelter capacity in the region will probably increase at a greater rate. If so, not all of the potential ammonium sulfate production from the Group I smelters could be sold to the available markets in 1975. However, the percentage that could not be sold would be small.

The justifiable markets for ammonium sulfate from the Group I smelters are not likely to increase as rapidly as the available markets between 1964 and 1975. The following tabulation summarizes for each of the three justifiable markets the average annual growth rate in consumption of ammonium sulfate between 1965 and 1975 and the resulting additional ammonium sulfate that could be consumed annually by 1975.

Future Ammonium Sulfate Consumption

Market	Estimated Annual Growth Rate 1965-1975 (percent)	Additional Use (1975) (1,000 tons/yr)
Southern California	2%	10
Arizona and New Mexico	3	10
West Texas	4	85
Total		105

The slow increase in Southern California is attributable to smaller increases in farm acreages, to a generally high existing rate of application of fertilizers with increased application rates being of marginal economic value, and to increased acidity of the commonly basic soils in the area resulting from the use of ammonium sulfate fertilizer. Some soils are now sufficiently acidic that increased use of ammonium sulfate might actually decrease crop yields. Ammonium sulfate use in Southern California in the future is expected to increase only about 2% annually, so 8,000 to 10,000 tons/yr more will be used in 1975 than in 1965.

The justifiable market for ammonium sulfate in Arizona and New Mexico is the same as the available market.

Of the three justifiable markets for ammonium sulfate from the Group I smelters, only the Texas market might use considerably more ammonium sulfate in the future. Consumption has increased 5-6% yearly over the past 10-15 years. A detailed examination of the future use of ammonium sulfate in Texas has not been made. However, it appears that use could increase 4%/yr at least to 1975. If so, 85,000 tons/yr more ammonium sulfate would be sold to this justifiable market by 1975.

The 105,000 tons/yr increase for the three justifiable markets would provide a total market of 327,000 tons, or enough to absorb only about 57% of the total potential 1965 production of ammonium sulfate from the Group I smelters.

Sulfur Dioxide

Essentially no available market exists for sulfur dioxide that might be produced by the Group I smelters. It is possible, however, that new uses will develop. Several organizations studying the leaching of copper ores have indicated that sulfur dioxide is as good as or better than sulfuric acid for solubilizing the copper values.

However, if sulfur dioxide is used for leaching it would merely be substituted for an equivalent amount of the sulfuric acid. As a result, no actual expansion of markets for smelter-produced sulfur by-products would occur but only a substitution of one product for the other. Under the circumstances, extensive work to determine the amount of sulfur dioxide that might actually be used is not justified.

Summary of Markets for Group I By-Products.

The data on the future markets that might be available for sulfuric acid, ammonium sulfate, and sulfur dioxide are summarized below.

Product	Estimated 1975 Market (1,000 tons)	Percent of Total Potential Production*
Sulfuric acid	1,560-1,860	41-49%
Ammonium sulfate		
available market	697†	100
justifiable market	327	57
Sulfur dioxide	not available	not available

Examination of the above data on future markets would indicate that at most 2.5 million of the 3.8 million tons of acid or acid equivalent currently recoverable from the Group I smelters could be sold. However, the markets for ammonium sulfate overlap those for sulfuric acid to the

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[*] Potential production in 1965. The percentages of the potential 1975 production will be even lower.

[†] Equivalent to 520,000 tons of sulfuric acid.

extent that sulfuric acid is sold to others to make ammonium sulfate. If these duplicate markets are only counted once, the equivalent of 1,740,000 to 2,040,000 tons of sulfur, i.e., acid from the Group I smelters, could potentially be sold in 1975, either as sulfuric acid or as ammonium sulfate. This would still represent only 51% to 60% of the current 3.8 million tons of sulfur equivalent available from these smelters. Therefore, at least half of the emissions from the Group I smelters must either be recovered as elemental sulfur or be removed in some nonsalable form if they are to be completely eliminated.

By-Products from Group III Smelters

Sulfuric Acid

The potential market for sulfuric acid from the Group III (Montana and Idaho) smelters existing in 1965 was 227,000 tons of a total possible production of 1.4 million tons. The potential market, by major end use, is as follows:

	Potential Consumption of Sulfuric Acid from Group III Smelters in 1965	
Market	Tons	Percent
Fertilizers	130,000	57%
Uranium processing	75,000	33
Leaching of ore and other markets	22,000	10
Total	227,000	100%

Therefore, additional markets for 1.2 million tons of sulfuric acid (or of sulfuric acid plus equivalent ammonium sulfate) are needed to permit the Group III smelters to recover all of the sulfur emitted from their stacks in 1968.

The first part of this section is directed toward a preliminary assessment of the practicality of developing outlets for this large amount of sulfuric acid in the production of phosphate fertilizer materials.

The reaction of sulfuric acid with phosphate rock to produce phosphoric acid is considered to offer real possibilities because large commercial deposits of phosphate rock are present in the region. These deposits are already being worked, especially in Montana, Idaho, and Utah, and the phosphate rock produced is either moved by rail to fertilizer plants in western Canada or is processed locally to phosphoric acid, which then is usually converted into more convenient forms of fertilizer such as triple superphosphate or ammonium phosphate. (Small amounts of phosphate rock are reacted with nitric acid to form solid fertilizers, and some phosphoric acid is used directly as liquid fertilizer; however, these uses are of little relative importance.) These products find primary markets within the western states and provinces, but some amounts are shipped eastward to those regions in which it is possible to compete with similar materials produced from Florida phosphate rock, Gulf sulfur, and low cost ammonia.

The study initially focuses on southwestern Montana, since that area's large potential for sulfuric acid and its proximity to commercial deposits of phosphate rock make it the most likely location for development of fertilizer phosphate-processing facilities. These facilities would most likely be directed toward production of phosphoric acid alone, since limiting production to this salable intermediate would allow maximum advantage to be taken of local materials. Effort is directed toward quantifying the market for phosphate fertilizers existing in the regions surrounding southwestern Montana, projecting its size to 1975, identifying the producers who depend on this area for their phosphate, and comparing the production cost of sulfuric acid and phosphoric acid at certain locations to demonstrate the extent of any economic advantage that could encourage production and sale of either sulfuric acid or phosphoric acid to phosphate fertilizer producers. Fundamental to this cost comparison is the assumption that sulfuric acid produced from smelter gases could be made available at a price of $9/short ton, f.o.b. the smelter, including a reasonable margin for profit. However, comparisons are also made based on the $4/ton price used throughout the earlier sections of this report.

Consumption of phosphate fertilizers in the states and provinces in or around the areas having deposits of phosphate rock and potential supplies of smelter-derived sulfuric acid is presented in Table 23 for the period between 1950 and 1967, together with projections to 1975 and the quantity of P_2O_5 to be consumed in that year over and above consumption in 1967. Projections are generally a continuation of growth at rates somewhat below those experienced by each area during recent years and do not reflect any extensive analysis of changing fertilization practices in these areas. The individual figures on projected additional P_2O_5 consumption by 1975 are plotted on Figure 3 for each area. It is seen that while sizable growth will take place in the Pacific Northwest and northernmost Mountain States, the largest increases are to be experienced in the provinces to the north and states to the east. These provinces and states have in the past been primarily supplied with P_2O_5 produced from phosphate rock mined in Montana, Idaho, and Utah, although the Dakotas and Nebraska are so located that competition from Florida-based P_2O_5 is strong. In the future it is expected that sizable amounts of P_2O_5 will enter the Pacific Northwest and western Canada in the form of phosphate rock moved by deepwater from Florida to processing plants in British Columbia and Alberta; however, P_2O_5 produced in the northern Mountain States will continue to fill most of the region's demand in future years.

By 1975, an increased P_2O_5 consumption of at least 300,000 short tons per year will develop within a radius of approximately 400 miles of the smelters in western Montana. Although a new producer of P_2O_5 in that area could hardly expect to capture a large share of this increment, current suppliers plus any new suppliers to this area will need around a million tons more sulfuric acid with which to produce P_2O_5 in these increased amounts. Smelter-derived sulfuric acid should find a ready market where it can be delivered at a lower value than sulfuric acid produced from elemental sulfur from Alberta. It would be fortunate if phosphate rock were available near the smelter so that phosphoric acid could be produced nearby in cooperation with an existing producer and consumer. The relative merits of these alternatives can best be evaluated after

Table F-23

CONSUMPTION OF P_2O_5 IN FERTILIZERS

(1,000 of short tons of P_2O_5)

Region and State or Province	1950	1955	1960	1965	1966	1967	1975 (projected)	Increase in Annual Consumption 1967-75
Pacific Northwest	75	97	142	199	195	228	371	143
Washington	9	14	20	33	38	38	77	39
Oregon	12	13	17	28	34	48	94	46
California	54	70	105	138	124	142	200	58
Mountain States	40	58	96	147	163	186	348	162
Montana	4	7	14	23	27	37	80	43
Idaho	10	12	24	37	41	44	88	44
Wyoming	2	3	4	6	8	9	15	6
Colorado	9	11	17	33	31	37	64	27
New Mexico	5	7	8	11	11	12	17	5
Arizona	7	14	22	24	24	25	38	13
Utah	3	4	7	11	20	20	38	18
Nevada	--	--	1	2	2	2	8	6
Western Canada	n.a.	n.a.	60*	142	198	225	700	475
British Columbia	n.a.	n.a.	5*	7	8	8	25	17
Alberta	n.a.	n.a.	29*	63	72	86	300	214
Saskatchewan	n.a.	n.a.	16*	51	76	86	275	189
Manitoba	n.a.	n.a.	10*	21	42	45	100	55
Other states								
North Dakota	5	22	48	70	85	100	230	130
South Dakota	1	9	7	18	28	33	100	67
Nebraska	5	27	27	60	80	106	280	174

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n.a. = not available.

* 1961 data.

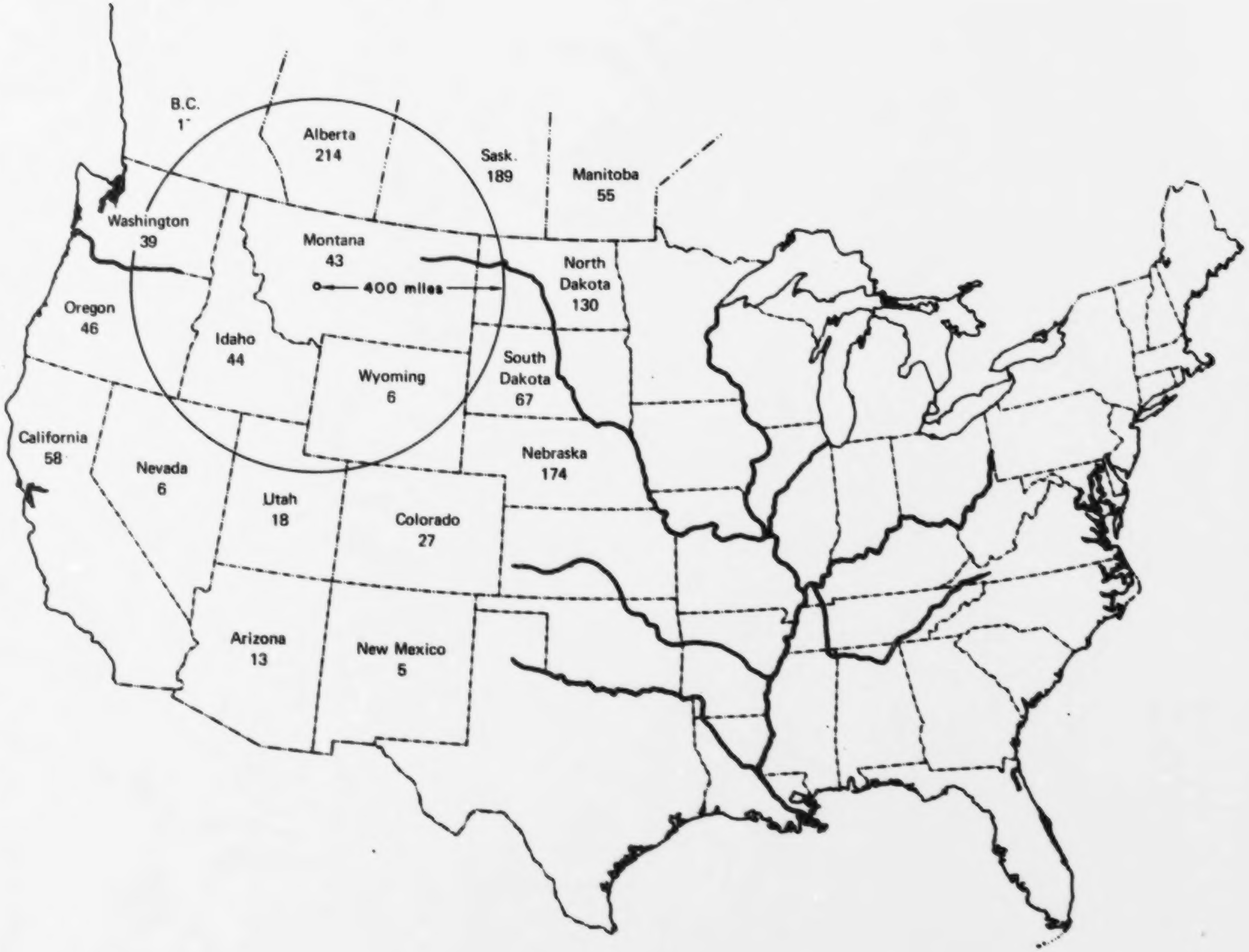
B.C.
1
Alberta
214
Sask.
189
Manitoba
55
Washington
39
Montana
43
400 miles
North
Dakota
130
Oregon
46
Idaho
44
Wyoming
6
South
Dakota
67
California
58
Nevada
6
Utah
18
Colorado
27
Nebraska
174
Arizona
13
New Mexico
5

FIGURE 3 ADDITIONAL P_2O_5 CONSUMPTION ANTICIPATED BETWEEN 1967 AND 1975
Thousands of Short Tons of P_2O_5

considering the locations of current phosphoric acid producers and of the phosphate rock mines that supply these operations.

There are 12 producers of fertilizer P_2O_5, in the western United States and Canada, who react phosphate rock with sulfuric acid to produce phosphoric acid. Small amounts of fertilizer P_2O_5 are produced by two or three others from elemental phosphorus or by reacting nitric acid with phosphate rock, but these are not of interest to this study since they are not large sulfuric acid users. Table F-24 presents data on the 12 phosphoric acid producers, including their locations, capacities, phosphate rock origins, and whether the phosphate rock they use is purchased or is from their own mines.

The current capacity for production of more than 900,000 short tons per year of fertilizer phosphoric acid (P_2O_5 basis) in the western United States and Canada is considerably in excess of the current market for 600,000 to 700,000 short tons per year in that area. While some quantities are moved out of the area into the states to the east, reducing the size of apparent overcapacity, no new capacity will probably be needed until well after 1970. However, additions to P_2O_5 capacity will be required before 1975, and in turn these additions will require additional sulfuric acid production.

It is apparent that the great bulk of P_2O_5 produced in the broad area comes from plants centered around phosphate rock deposits of the southeastern Idaho-western Wyoming-northern Utah area and from plants near low cost sulfuric acid in southeastern British Columbia and southern Alberta. While a good portion of the phosphoric acid produced in the first area is based on sulfuric acid recovered from local smelters, most of the volume derives from elemental sulfur shipped into the area through western Montana from Alberta. On the other hand, much of the phosphate rock consumed by Canadian processors either originates in western Montana or moves through that area on its way from mines in Idaho and Wyoming.

The smelters most likely to make major contributions to filling the increased need in the area are those located in southwestern Montana, which are situated on the route of southbound movement of Alberta sulfur to the

Table F-24

PRODUCERS OF FERTILIZER PHOSPHORIC ACID IN THE WESTERN UNITED STATES AND CANADA*

Company	Location	Phosphate Rock Source	Status of Phosphate Rock Supply	Capacity (1,000 of short tons per year of P_2O_5)
El Paso Natural Gas Products	Conda, Idaho	Idaho	Own	100
Bunker Hill†	Kellogg, Idaho	Idaho	Purchased†	25
J. R. Simplot	Pocatello, Idaho	Idaho	Own	265
Western Phosphates‡	Garfield, Utah	Utah & Wyoming	Own	105
Cominco	Trail and Kimberley, B.C.	Montana & Idaho	Own and purchased	200
Sherritt Gordon Mines	Fort Saskatchewan, Alta.	Florida	Purchased	44
Western Cooperative Fertilizers	Calgary, Alberta	Florida	Purchased	57
Northwest Nitro-Chemicals	Medicine Hat, Alberta	Wyoming	Purchased	52
Imperial Oil§	Red Water, Alberta	Florida	Purchased	n.a.
Best Fertilizers**	Lathrop, Calif.	Florida	Own	17
Valley Nitrogen Producers	Helm, Calif.	n.a.	Purchased	50
Western States Chemical	Port Chicago, Calif.	n.a.	Purchased	9
Total				924

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* Excluding those whose production is based on nitric acid or elemental phosphorus.

† Cooperative project with Stauffer Chemical, owner of phosphate-rock supplier, S.F. Chemical.

‡ Owned by Stauffer, owner of phosphate-rock supplier, S.F. Chemical.

§ Under construction.

** Owned by Occidental Chemical, phosphate-rock producer.

phosphoric acid producers in southeastern Idaho; those near western Montana phosphate rock that moves to British Columbia; and those on the route of phosphate-rock movements from the mines of the Idaho-Wyoming-Utah intersection to phosphoric acid producers in British Columbia and Alberta. Therefore, consideration should be given to the possibility of:

1. Movement of sulfuric acid from Montana smelters to phosphoric acid plants in southeastern Idaho to compete with sulfuric acid derived from Canadian elemental sulfur.
2. Production of phosphoric acid in southwestern Montana by or in cooperation with any current producer or consumer of phosphoric acid that might realize some economic incentive from production near the smelter for shipment to another location for further processing.

In view of the relative locations of phosphoric acid producers and raw materials for their use, locations selected for initial comparison of production costs are Medicine Hat, Pocatello, and Butte. Selection of these locations is not intended to imply preference for any particular company located there; the choice is made to illustrate the economics of (1) a location close to elemental sulfur but distant from phosphate rock, (2) a location close to phosphate rock but distant from elemental sulfur, and (3) a location close to smelters with large recovered sulfuric acid potential and through which phosphate rock and sulfur pass as they go between the other two areas.

The fundamental assumptions, which reflect current prices and transportation charges in effect in those situations where materials move on a merchant basis, are as follows:

1. Elemental sulfur prices will decline by 1975 to $22.30 per short ton ($25 per long ton) f.o.b. several points in Alberta. Transportation charges will be $1 per short ton to Medicine Hat and $13 per short ton to Pocatello.
2. Sulfuric acid will be available at the smelters near Butte at a price of $9 per short ton, including a reasonable markup for profit and expenses of marketing. Transportation charges to Pocatello will be $6 per short ton. The cost of producing sulfuric acid from elemental sulfur will be $2 per short ton above the cost of the one-third short ton of sulfur required

per short ton of sulfuric acid. This includes no markup for profit but does include a charge for return of capital.

3. Phosphate rock of 33% P_2O_5 content will be available in southeastern Idaho at $8.85 per short ton. Transportation charges will be $1 per short ton to the Pocatello plant, $4 per short ton to Butte, and $5.60 per short ton to Medicine Hat. Although phosphate rock is not currently available in western Montana on a merchant basis, it is assumed for the sake of comparison that 33% P_2O_5 rock could be made available from captive mines near Butte at $8.85 per short ton and that transportation to Butte would be $2 per short ton.

4. Phosphoric acid transportation from Butte to Pocatello will be $6 per short ton and $10 per short ton from Butte to Medicine Hat.

In Table F-25, cost comparisons have been made of the various combinations of locations and raw materials of interest. Butte would have the lowest cost sulfuric acid and phosphoric acid under any set of conditions. While Butte phosphoric acid from Idaho rock could not be delivered to Medicine Hat at any saving over the location's current phosphoric acid cost, a saving of about 5% (due to less expensive raw materials) would be enjoyed if Butte were in a position to ship phosphoric acid made from Montana phosphate rock. Montana rock is unlikely to become available at Butte, however, unless new deposits are located or unless Cominco, which consumes the output from Montana, should recognize some advantage from cooperating in a local phosphoric acid operation. Northwest Nitro-Chemicals' Medicine Hat operation might benefit from having its shipments of phosphate rock from Idaho processed to phosphoric acid while in transit through Butte; however, this saving would not be great.

Supplies from Butte of sulfuric acid or of phosphoric acid made from Idaho phosphate rock would not appear attractive for use by Simplot or El Paso Natural Gas Products, the two operators in the Pocatello area, under the conditions proposed for 1975. Butte phosphoric acid from Montana phosphate rock offers some apparent attraction; however, since these two producers mine their own phosphate rock in Idaho and would have to forego the profit on phosphate rock production if Montana phosphate rock were

Table F-25

RAW MATERIAL COSTS FOR PRODUCTION OF PHOSPHORIC ACID (54% P_2O_5)
BUTTE VS MEDICINE HAT VS POCATELLO

	Dollars Per Short Ton of Material			Per Short Ton of P_2O_5		
	F.O.B. Origin	Trans-portation	Total	Units	Cost	Total
At Butte						
Idaho rock	$ 8.85	$ 4.00	$12.85	3.2	$41.10	$65.40
Own H_2SO_4	(from smelter gases)		9.00	2.7	24.30	59.00
Montana rock	8.85	2.00	10.85	3.2	34.70	
At Medicine Hat						
Idaho rock	8.85	5.60	14.45	3.2	46.25	72.55
Own H_2SO_4	(22.30	1.00)*	9.75†	2.7	26.30	
Butte phosphoric acid (from Idaho phosphate rock)	65.40	10.00	75.40	--	--	75.40
Butte phosphoric acid (from Montana phosphate rock)	59.00	10.00	69.00	--	--	69.00
At Pocatello						
Butte H_2SO_4	9.00	6.00	15.00	2.7	40.50	72.00
Idaho rock	8.85	1.00	9.85	3.2	31.50	68.70
Own H_2SO_4	(22.30	13.00)*	13.75†	2.7	37.20	
Butte phosphoric acid (from Idaho phosphate rock)	65.40	6.00	71.40	--	--	71.40
Butte phosphoric acid (from Montana phosphate rock)	59.00	6.00	65.00	--	--	65.00

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* Elemental sulfur.

† Cost of 0.333 short tons of sulfur plus $2.00.

substituted, Butte phosphoric acid would be of interest to them in Pocatello only as a supplement to local production. The degree of attraction to any of these phosphoric acid producer-marketers could be enhanced if shipment of Butte phosphoric acid could be made directly to distant locations where phosphoric acid is needed, rather than to the locations where phosphoric acid is now produced.

Butte's marketing position would be strengthened if a price lower than $9 per short ton were acceptable for sulfuric acid or if transportation costs to Medicine Hat or Pocatello were reduced. If, for example, the price of the smelter-produced sulfuric was $4/ton instead of $9/ton, the total cost per ton of P_2O_5 produced would be reduced $13.50 in each instance where this acid is used to make the fertilizer. The resulting total raw materials costs in these situations would range from $45.50/ton P_2O_5 for Montana rock treated with smelter acid to produce phosphoric acid sold as fertilizer at Butte, to $61.90/ton P_2O_5 for Idaho rock and smelter acid to produce phosphoric acid to sell at Medicine Hat. None of the alternative approaches to producing phosphoric acid using nonsmelter acid could compete against such prices. Savings through use of jumbo tankcars, unit trains, and even a sulfuric acid pipeline between the smelter area of Montana and the phosphate rock-mining area of Idaho might provide added incentive for cooperation between the smelters and the phosphoric acid producers.

Concentration of the normal 54% P_2O_5 content phosphoric acid to superphosphoric acid of about 72% P_2O_5 content also could improve Butte's economic position, especially in the case of material to be shipped over considerable distances. Production of superphosphoric acid of 68%-72% P_2O_5 content costs about $7/short ton of P_2O_5 above the cost of 54% acid at a production level of 200 short tons per day of P_2O_5. The cost of transporting 72% P_2O_5 acid to Medicine Hat at $10 per short ton of product acid would amount to $13.90 per short ton of P_2O_5, a freight reduction of $4.60 from the $18.50 per short ton P_2O_5 for 54% P_2O_5 acid. In this example the additional cost of concentration would exceed freight saving by some $2.40 per short ton of P_2O_5, making superphosphoric acid appear less attractive for this movement. However, transportation savings with superphosphoric acid would increase with the length of haul and, at an assumed 2 cents per ton mile rate, a haul of some 775 miles would allow superphosphoric acid freight savings to equal the additional cost of concentrating the acid. Furthermore, the use of superphosphoric acid in place of regular phosphoric acid for production of compounds with ammonia reportedly allows economies of production of several dollars ($2 to $10) per ton of ammonium phosphates produced. This is because of both the lower water content of superphosphoric acid and changes in chemical composition that offer certain product improvements. On this basis, even consumers located closer to the superphosphoric acid plant than the estimated 775 mile radius might prefer shipments of superphosphoric acid in place of regular phosphoric acid. Further study of the phosphoric acid-superphosphoric acid economic relationship should be made before definite conclusions are drawn.

Under any circumstances, consumers of phosphoric acid in locations more distant than Medicine Hat would be better prospects for Butte phosphoric acid than Medicine Hat because of their greater distance from both phosphate rock and sulfur or sulfuric acid. For example, the plants at Regina, Saskatchewan, or Brandon, Manitoba, are now supplied with phosphoric acid that originates as phosphate rock from Montana or Idaho and as sulfur from Alberta or smelter acid from British Columbia. Since these two locations are satellite plants of Cominco and Simplot, respectively, cooperation with either or both of these producers would be required.

While production of ammonia for conversion of phosphoric acid to ammonium phosphates might be worth consideration at a later date, it is believed that this is likely to prove unrewarding because ammonia produced from natural gas in southwestern Montana would be relatively expensive and would tend to reduce the extent of the local cost advantage. Further, while phosphoric acid probably could be marketed to fertilizer producers in locations with low cost ammonia, efforts to produce combinations with ammonia for sale in competition with these producers would meet considerable resistance, especially in view of the current large overcapacity situation in the fertilizer industry.

To summarize briefly, phosphate fertilizer consumption in the area depending on the northern Mountain States and western Canadian provinces for supplies of this plant food will increase between 1967 and 1975 by more than 300,000 short tons of P_2O_5 annually. This increase is greater than the P_2O_5 content of the quantity of phosphoric acid that could be made from the approximately one million short tons per year of sulfuric acid potentially available from waste gases of smelters operating in the northern Mountain States. Under appropriate economic conditions, a large part of this amount of sulfuric acid could be used, especially by those local phosphoric acid producers who are distant from supplies of Alberta elemental sulfur, but also by those more distant phosphoric acid producers who depend on phosphate rock mines in the general smelter area.

Uranium processing also represents an increasing potential market for sulfuric acid from the Group III smelters. According to AEC estimates, large increases in the use of sulfuric acid for this purpose will occur in eastern Washington (54,000 tons/yr) and in Wyoming (96,000 tons/yr) by 1975. The increased use of acid in these areas plus any increases in use by the AEC at Hanford, Washington,could provide markets for an additional 150,000 tons of Group III smelter acid by 1975.

Therefore, barring any unusually large expansions in the capacities of the Group III smelters, it is potentially possible to develop existing markets sufficiently to permit these smelters to recover nearly all of their emissions either as sulfuric acid (or as a combination of sulfuric acid and ammonium sulfate).

By-Products from Groups VI and VII Smelters

Sulfuric Acid

The potential market for sulfuric acid from the Groups VI and VII smelters was 109,000 tons in 1965 as compared with a total possible production of 234,000 tons. The imbalance between potential markets and production is small (125,000 tons/yr) when compared with the differences between markets and production in the Group I or III smelter-market regions. However, reduction or elimination of this imbalance is equally, if not more, important in the case of the Group VI and VII smelters because of their proximity to large metropolitan areas.

Unfortunately, it was not known that potential acid production exceeded acid markets until the final revised data on smelter emissions was submitted in March 1969. As a result, no time was left to examine the future markets for acid in the vicinity of these smelters. Thus, no indication can be given as to the reduction in emission that might be accomplished through the mechanism of increased recovery and sales of acid from these smelters.

Ammonium Sulfate

The manufacture and sale of ammonium sulfate does appear to provide an opportunity to reduce the emissions from the Groups VI and VII smelters. As indicated in the section on ammonium sulfate, 19,000 tons/yr could be manufactured by treating the dilute waste gas streams. Markets should absorb this entire production if the smelters would sell the by-product for $33/ton or less. However, the local market could use about another 56,000 tons of ammonium sulfate at the same price if it were available. The market in the region might use a total of 75,000 tons/yr of smelter-produced ammonium sulfate, which would be equivalent to the use of 56,000 tons of sulfuric acid, reducing the imbalance between potential production and markets of sulfuric acid to around 70,000 tons/yr.

Very little if any growth is expected in this ammonium sulfate market because large quantities of urea will soon become available to supply nitrogen needs. Since more ammonium sulfate is being used at present than is needed to supply the sulfur required by the crops grown in the area, the availability of a more concentrated form of fertilizer nitrogen will probably prevent the market for ammonium sulfate from increasing. Therefore, markets for other by-products (sulfur or sulfuric acid) must be developed or nonsalable products must be produced if the Groups VI and VII smelters are to eliminate their sulfur dioxide emissions.

APPENDIX G

LITERATURE REVIEW

CONTROL OF SULFUR OXIDE EMISSIONS FROM PRIMARY COPPER, LEAD, AND ZINC SMELTERS

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Appendix G

LITERATURE REVIEW

CONTROL OF SULFUR OXIDE EMISSIONS FROM PRIMARY COPPER, LEAD, AND ZINC SMELTERS

Introduction

The history of attempts to control sulfur oxide emissions from copper smelting, in order to reduce air pollution, goes back at least 150 years (2A). Manufacture of sulfuric acid from copper smelter gases was undertaken in Great Britain at least 100 years ago, partly in response to a need to control air pollution (2A). It is noteworthy that one of the major technical problems of that time -- dealing with lean sulfur dioxide streams too dilute to be used directly in manufacture of sulfuric acid -- is still the major technical problem today.

The history of the development of zinc ore roasting is closely associated with both air pollution problems and the development of the chemical industry with its attendant demand for sulfuric acid (13C). The first plant for making sulfuric acid from zinc roaster gases was built in Germany in 1855 (13C). Muffle furnaces were constructed that produced offgases containing relatively high concentrations of sulfur dioxide (4 to 7 percent) for use in chamber-process acid plants (5C, 7C). Reverberatory roasting furnaces produced gases low in sulfur dioxide content (1 percent or less) that were discharged to the atmosphere (5C). However, by 1889 the offgas from a zinc smelter in Germany, containing 1 percent of sulfur dioxide, was being scrubbed in spray towers with milk of lime (3A, 5C).

There is precedent for control of all the general types of sulfur oxide emissions from smelters, including lean streams. The principal barrier to control has been economic rather than technical. Technically feasible methods for control have existed for years, and have been applied when the air pollution problems have been sufficiently critical to outweigh the normal economic considerations. In all but a few cases the sulfur dioxide has been recovered as sulfuric acid, but in some instances where markets were not available for all of the potential production of sulfuric acid, elemental sulfur has been produced (4A, 5A, 33F). Liquid sulfur dioxide has been produced only to satisfy available markets (17F). The concentration of sulfur dioxide has otherwise been practiced only as a necessary preliminary to use of the gas in sulfuric acid manufacture or to its reduction to elemental sulfur (4A, 5A). Direct production of ammonium sulfate from smelter stack gases has resulted from the use of aqueous ammonia as an absorbent in concentrating sulfur dioxide from lean streams (5A, 7A). Where the gas streams are rich enough in sulfur dioxide to be used directly in manufacture of sulfuric acid, it is evidently cheaper to produce ammonium sulfate by reaction of the acid and ammonia than it is to do so by waste gas scrubbing.

It has been customary for smelters to recover only as much sulfur (as sulfuric acid) as they could sell to available markets or as they needed for use in their own operations (1A, 26D). However, where the necessity for air pollution control dictated recovery of a large fraction of the sulfur oxides, smelters have sometimes had to exert major efforts to create or develop markets for their sulfur by-products (8A). In the two most notable instances of this kind involving the smelters at Ducktown, Tennessee and Trail, British Columbia, it was the manufacture of fertilizer that eventually permitted disposal (8A). At the Trail smelter, production of elemental sulfur was an interim measure that was abandoned as soon as sufficient markets for sulfuric acid became available (5A).

Because of the critical nature of the relationship between the cost of sulfur by-product recovery, the concentration of sulfur dioxide in the waste gas, and the volume of the waste gas, the nature of the metallurgical process has in turn a crucial influence upon the economics of sulfur recovery. Large volumes of waste gases have been scrubbed to recover sulfur dioxide present at low concentrations (5A, 30F). Nevertheless, where sulfur dioxide recovery has been desired, measures have usually been taken to reduce the volume of waste gas and thereby to increase the sulfur dioxide concentration. In some cases this has been accomplished in part by reducing air infiltration into the waste gas system; in others, changes have been made in the metallurgical processes themselves. In the latter instances, technical and economic benefits in the process have usually been sought, as well as reduction in the cost of sulfur oxide recovery or emission control.

Lead Smelting

In U.S. lead smelting practice, the only operation that is a major source of sulfur oxide emission is the roasting of the lead sulfide ore concentrates, which is combined with sintering. The combined sintering and roasting operation is carried out on sintering machines of the Dwight-Lloyd downdraft type, or--more recently--on machines of the updraft type (5B, 11B).

With the unmodified downdraft Dwight-Lloyd machines there is a large amount of air inleakage into the offgas, diluting the sulfur dioxide to concentrations in the general range of 1 to 3 percent (6B, 9B, 10B). Consequently, the gases cannot be used directly in an autothermal contact sulfuric acid plant. At the Trail, B.C. smelter of Cominco, Ltd., the sulfur dioxide in the lead sintering machine gases has been concentrated and recovered by scrubbing with aqueous ammonia (5A, 30F). However, methods for recirculating a major portion of the offgases were developed and applied over 25 years ago (9B), and it was thereby possible to produce a waste gas stream containing 4 to 7 percent of sulfur dioxide that could be used as feed to an acid plant. Apparently part of the original impetus for development of recirculation of gases was simply the reduction of the volume of gases that had to be cleaned, even before sulfur dioxide recovery was undertaken (9B).

Within about the last decade, updraft sintering has been developed abroad (11B), and it is now going into use in U.S. lead smelters (1B, 5B). The updraft sintering process not only has numerous major advantages from a purely metallurgical process viewpoint, but also cuts down the infiltration of atmospheric air, so that the offgas is reduced in volume and enriched in sulfur dioxide (11B). By use of gas recirculation it is possible to concentrate all of the sulfur dioxide released into the relatively rich gas stream and to attain sulfur dioxide concentrations of about 5 to 7 percent (5B, 11B). The new Gibson smelter will use updraft sintering with gas recirculation and will manufacture sulfuric acid from the offgas (5B). The Bunker Hill Co. is converting older downdraft sintering machines to updraft, and will use the enriched offgases (7 percent sulfur dioxide) to produce sulfuric acid (1B).

The lead blast furnace is a relatively minor, but apparently highly variable source of sulfur oxide emissions. In 1936, Oldright and Miller (8B) reported sulfur dioxide concentrations in the top gases from blast furnaces in three lead smelters. The concentrations at one furnace varied from 0.005 to 0.018 percent and those at another from 0.018 to 1.22 percent. In the third furnace, the range was 0.08 to 6.05 percent, with an average of about 1.5 percent.

In the more distant future, processes for directly smelting lead sulfide concentrates to the metal are likely to be developed and commercialized (7B). The roasting and sintering process would be eliminated. The St. Joseph Lead Co. has been carrying out pilot plant tests of a converter in which the concentrates are smelted autogenously by air blowing (4B). The offgases from the pilot plant contained from 13 to 14 percent of sulfur dioxide. Bryk et al. (2B) have described a flash smelting process for lead concentrates that has been tested on a pilot plant scale by Outokumpu Oy in Finland. The offgases from the furnace contained 10 to 12 percent of sulfur dioxide.

The Boliden Company in Sweden has developed and placed in commercial operation a process for direct smelting of rich lead sulfide concentrates in an electric furnace (3B). The offgas from the electric furnace, containing 6.0 percent of sulfur dioxide (8.5 percent leaving the waste heat boiler), is used to manufacture sulfuric acid. The molten lead tapped from the electric furnace still contains a small amount of sulfur, and is blown with air in a converter for removal of the residual sulfur and separation of dross. The additional sulfur dioxide generated in the converter is not recovered.

Zinc Smelting

There are two significant sources of sulfur oxides emissions in zinc smelters: the roasters and (where used) the sintering machines. The sintering machines are used to agglomerate roasted ore so that it can be reduced to the metal by one of the thermal reduction processes (6C, 8C). In the sintering process residual sulfur remaining in the calcined ore is eliminated (8C). In electrolytic zinc plants the ore is dead roasted to eliminate sulfide sulfur, but sintering is unnecessary (7C).

Most U.S. zinc smelters produce sulfuric acid from roaster gases. Some of the roasters are of the multiple-hearth type, but these are being superseded by the more modern suspension or fluidized-bed types (2C, 3C, 8C, 12C). The multiple-hearth roasters produce offgases containing up to 6 percent or more of sulfur dioxide, dependent upon the type of operation (8C). The suspension roasters produce offgases containing 9 to 10 percent of sulfur dioxide (2C, 8C), or higher levels when the gases are recirculated and enriched with oxygen (9C). Fluidized-bed roasters may produce offgases containing up to 14 percent sulfur dioxide when used for a partial roast, or 9 to 10 percent in a dead roast (37D).

The fluid-column roasters developed by the New Jersey Zinc Co. produce offgases containing 10 to 12 percent of sulfur dioxide (1C, 4C, 11C). This process has been used abroad previously (1C, 8C), but the first such unit is now going into service in the U.S. (4C). The feed to the roasters is pelletized, and so is the calcined product, which does not have to be further agglomerated by sintering.

In the small number of instances where sulfuric acid is not produced from zinc roaster gases, no attempt is made to produce rich offgases. At the Anaconda Company plant at Great Falls, Montana, the ore concentrates are roasted in multiple-hearth roasters for subsequent direct leaching in the electrolytic zinc process. Large volumes of oxidizing air are used to eliminate sulfur while keeping down the temperature to reduce zinc ferrite formation and prolong the life of the equipment, and the offgases contain only 1.5 percent of sulfur dioxide (8C). Such conditions are conducive to conversion of a relatively large amount of the sulfur dioxide to sulfur trioxide (13F). Both the equipment and the method of operation described by McBean in 1959 (8C) appear to be old, since the description coincides very closely with that given of the same plant by Hofman in 1922 (5C).

Combined roasting and sintering of ore concentrates is practiced at the Blackwell, Oklahoma smelter of the Blackwell Zinc Company, using a modification of the Robson process (6C, 8C). The operation is carried out on a downdraft sintering machine. The offgases are discharged to the atmosphere and a high concentration of sulfur dioxide in the waste gas is not desired (8C). However, part of the gases from the sintering machine are recirculated in order to reduce the volume of waste gas that must be filtered in the baghouse (6C). As used in Great Britain and Germany, the Robson process employs gas recirculation to attain a sulfur dioxide concentration of 6.5 percent, permitting use of the exhaust gas in a sulfuric acid plant (8C).

Ropp furnaces are used for roasting of concentrates at the Amarillo, Texas smelter of American Smelting and Refining Company (8C) and the Dumas, Texas smelter of the American Zinc Company. The Ropp furnace is an obsolete device reported in the literature to produce offgases containing about 1 percent of sulfur dioxide (5C).

The waste gases from sintering machines sintering calcined zinc ores presumably contain low but highly variable concentrations of sulfur dioxide dependent upon the type of sinter desired and the amount of residual sulfur remaining in the calcined ore (8C). The sintering machine gases at the Amarillo smelter are reported to contain about 1 percent of sulfur dioxide (8C).

McBean (8C) reports that the biggest item in sintering costs is connected with materials handling in the recycling of huge tonnages of sinter and that the large circulating loads are inevitable with existing designs and practices if good sulfur elimination and the desired quality of final sinter are to be attained. He suggests that reduction in the volumes of exhaust gases should reduce both installation and operating costs, permitting use of smaller flues, fans, and dust collectors. Reduction of air infiltration by use of updraft sintering and gas recirculation are suggested as methods. McBean also suggests use of oxygen-enriched air to increase unit capacity, produce relatively small volumes of exhaust gases rich in sulfur dioxide, reduce fuel consumption, and possibly afford heat recovery.

Copper Smelting

In conventional U.S. copper smelting practice (1A, 11D, 19D), there are three major sources of sulfur oxide emissions: (1) roasters (where used), (2) reverberatory furnaces, and (3) converters. Recovery of sulfur oxides from the roaster gases is essentially the same as recovery from the offgases of zinc roasters. However, recovery from the reverberatory furnace gases and converter gases is much more difficult. The reverberatory furnace gases commonly contain only 1 to 2 percent of sulfur dioxide (1A, 11D), and this concentration level is inherent in the process and is not due to air infiltration as it frequently is in other processes. Converting is a batch process in which the flow rate and sulfur dioxide concentration of the offgas vary widely with time, and a staggered operating schedule with two or more units is necessary to provide a reasonably consistent gas stream for treatment in a recovery process (33F, 44F). Over most of the cycle of converter operation, the offgases are rich in sulfur dioxide, but a large amount of dilution takes place due to infiltration of atmospheric air (44F).

The development of new technology for copper smelting has been quite rapid in recent years (24D, 34D, 40D), and the application of some of this new technology can have major influences on the reduction of sulfur oxides emissions.

Roasting

During the past 30 years there has been a trend toward direct smelting of green-ore concentrates in the reverberatory furnace and consequent elimination of the roasters (11D, 19D), but a reversal of the trend is now taking place (19D). In roasting of copper ores, only part of the sulfur is removed (37D, 38D). In the older plants, the roasters are of the multiple-hearth type and produce offgases containing up to about 7 percent of sulfur dioxide (44F). Roaster gases have been used for sulfuric acid production (9D, 37D, 44F). Where converter gases have also been used to make sulfuric acid, the roaster gases have sometimes been used to enrich the converter gases and provide more stable operation of the acid plant (5D, 44F).

The revival of interest in roasting coincides with increased interest in acid production and air pollution control (19D). The new fluid-bed type of roasters operate autogenously and the offgases contain up to about 15 percent of sulfur dioxide (9D, 38D). Roasting eliminates sulfur that would otherwise be driven off in the reverberatory furnance and converters, and smelter capacity can be increased (9D).

With fluid-bed roasters it is possible, by using excess air and careful temperature control, to selectively convert the copper sulfides to copper sulfate without converting iron present to a soluble form (33D, 35D, 36D, 39D). The roaster gases contain about 7 to 8 percent of sulfur dioxide (9D, 38D). The copper can then be leached from the calcine and recovered by electrowinning, eliminating the conventional reverberatory smelting and converting steps with their attendant release of sulfur oxides. This process is analogous to that of an electrolytic zinc plant. This process has been used abroad, primarily for complex ores from which it is desired to recover zinc or cobalt as well as copper (18D, 34D, 35D, 36D, 39D). However, such a process was tested in the U.S. on a pilot-plant scale for possible use on mixed oxide and sulfide-type copper ores (15D). The adoption of this type of system in one Japanese smelter was at least partly motivated by the need to control air pollution (18D).

Smelting

The concentration of sulfur dioxide in the offgases from conventional reverberatory copper smelting furnaces has been given as 1 to 2 percent (1A, 11D) and as 1 to 3 percent (8D). Short of changing the process, there is no chance to increase these concentrations substantially.

However, alternative processes do exist, and others are under development. Increases in smelting capacity and reduction in fuel use have been major objectives of these developments (12D, 16D).

One of the most direct steps is the use of oxygen or oxygen-enriched air in an essentially conventional reverberatory furnace. Oxygen has been used in reverberatory furnaces to increase the rate of smelting (34D). International Nickel Company (30D) is employing oxygen-enrichment on a commercial basis in the reverberatory smelting of cupriferous nickel ores. The Kennecott Copper Corporation has made pilot-scale tests of oxygen injection into a reverberatory furnace, using roof lances analogous to those used in open hearth steel furnaces (8D, 44D). In the pilot furnace tests, sulfur dioxide concentrations in the offgases ranged from 12 to 18 percent (8D).

Outokumpu Oy developed a largely autogenous flash smelting furnace, using preheated air, which has been in commercial operation in Finland since 1949 and in Japan since 1956 (12D). The offgases from the furnace contain 11 to 14 percent of sulfur dioxide, and are used in manufacture of sulfuric acid (12D, 27D). The concentrate fed to the furnace has to be dried well in advance, and because a high grade matte is produced, the losses of copper in the slag are relatively high and a separate slag cleaning operation must be employed (12D, 27D). However, the use of the high grade matte is reported to afford savings in the converter operation.

The International Nickel Co. (16D) has operated an autogenous flash smelting system for nickeliferous copper concentrates on a commercial basis since 1952. Commercially pure oxygen (about 95 percent) is used instead of air, and the offgases contain 75 to 80 percent of sulfur dioxide (2D, 21D). The balance of the offgas consists primarily of nitrogen (16D). After being cleaned and cooled, the offgas is compressed and most of the sulfur dioxide is removed as a liquid; the small flow of noncondensible tail gas, which is still saturated with sulfur dioxide vapor, is piped to a sulfuric acid plant (2D, 21D).

Where cheap electric power is available, electric furnace smelting possesses certain advantages over reverberatory smelting (1A, 7D, 13D, 26D). Heat losses are lower, and generation of large volumes of hot, dust-laden gases is avoided (13D, 26D). The offgas from the electric furnace consists primarily of the gases generated from the charge, water vapor, and air leaking into the furnace (7D). If a tight furnace enclosure is maintained to keep down the air inleakage, the volume of the offgas can be kept low, reducing the size of the gas handling and gas cleaning installation. In addition, the concentration of the sulfur dioxide in the waste gas can be kept high, reportedly 10 to 20 percent (26D).

Electric furnaces are not employed for copper smelting in the U.S., where fuel for reverberatory smelting is plentiful and relatively cheap, but they are used abroad, particularly in the Scandinavian countries (7D, 13D). There is, however, no obvious reason why they could not be used under favorable conditions in the U.S., just as they are in the steel industry.

It is possible to reduce the proportion of the sulfur that is driven off in the reverberatory furnace by, for example, preliminary roasting (9D). With the introduction of oxygen-enriched air into the converter, it is possible to carry out smelting as well as converting in the converter itself (4D, 17D). Hence it is necessary to smelt only a part of the ore concentrate in the reverberatory furnace to provide the initial charges to the converters at the start of an operating cycle (41D).

Converting

Because copper converting is a batch process, the output of sulfur dioxide from a converter varies with the portion of the converter cycle. No gas is produced during periods in which the converter is being charged, slag is being skimmed, or copper is being poured (44F). When sulfuric acid is to be made from the sulfur dioxide, at least two, and preferably more, converters must be in operation on cycles so scheduled that there is an adequate flow of gas to the acid plant at all times (33F, 44F).

The concentration of sulfur dioxide in the gas evolved from the converter depends upon the stage of the blowing cycle. It reaches a theoretical maximum of 21 percent during the finish stage, when the "white metal" (cuprous sulfide) is converted to copper metal (44F). During earlier stages of blowing, when iron sulfide is being oxidized and fluxed to form slag, the theoretical sulfur dioxide concentration in the offgas is about 14 percent (44F). However, such concentrations appear in the offgas only inside the converter mouth. The emerging gas is diluted by atmospheric air entering the gas handling system at the converter hoods and the flues (33F, 44F). As a result, the sulfur dioxide concentration in the gases from a converter plant is usually low by the time the gases reach the acid plant. With conventional practice as employed in the U.S. and in numerous smelters abroad, the sulfur dioxide concentration may vary from about 3 to 8 percent at different stages of the converter cycles, and averages about 4 to 5 percent (4D, 14D, 44F). As the number of converters in operation is increased, it becomes easier to maintain a steady sulfur dioxide concentration level in the offgases.

Most of the infiltration of air takes place at the hood covering the mouth of the converter, where a tight enclosure is not usually maintained. It is common practice deliberately to permit infiltration in order to cool the hot converter gas and prevent damage to the hood and unlined metal flues (22D). However, in some smelters abroad, water cooling is used to protect the converter hoods (22D) and waste heat boilers are used to cool the gases and recover heat (14D, 22D, 25D). Tighter hooding of the converter mouths has reduced the infiltration of air, reducing the load on dust collection equipment and increasing the sulfur dioxide concentration (22D, 25D). At the Onahama smelter in Japan (25D), waste heat boilers are used behind each of the three converters. Although air is allowed to enter the system in order to provide a sufficient excess of oxygen for subsequent conversion of the sulfur dioxide to sulfur trioxide, the sulfur dioxide concentration in the gas reaching the sulfuric acid plant is 6 to 9 percent (25D). An additional advantage (see below) of the use of waste heat boilers is that the gases are rapidly cooled in the absence of a great excess of air, restricting conversion of sulfur dioxide to sulfur trioxide before the sulfuric acid plant is reached (25D).

The problem of hooding copper converters is similar to that of hooding basic oxygen furnaces (BOF) in the steel industry (10D). Major improvements in hooding BOFs have been made in recent years. Systems have been devised that prevent infiltration of air into the BOF offgases, so that the carbon monoxide gas is not burned (1D, 23D, 29D, 32D). Not only is the volume of gas that must be cleaned greatly reduced, but the carbon monoxide can be recovered for subsequent use as fuel. If an analogous system were applied to copper converters, it should be possible to collect a gas stream that would be only slightly diluted and should contain sulfur dioxide at concentrations approaching the theoretical range--perhaps 10 to 18 percent.

The use of oxygen-enriched air in converters was first introduced commercially in Japan (41D), and has been in limited use in the U.S. for several years (24D). The Garfield smelter of the Kennecott Copper Corp. is now being modified to employ oxygen-enriched air in the converters (4D). The theoretical concentration of sulfur dioxide in converter gases increases in proportion to the percentage of oxygen in the air used in blowing the converter. At the Garfield smelter, the concentration of sulfur dioxide in the gas stream is expected to rise from the present 4 percent to 6 percent (4D), affording a large increase in the capacity of the acid plant. Presumably the rise in sulfur dioxide concentration will not be aided by any major increase in the tightness of the hood system. At the Hitachi smelter, which also employs oxygen enrichment and converter smelting, the percentage of sulfur dioxide in the converter gases is reported to range from about 10.5 to 20 percent (42D).

If oxygen enrichment of the blast to the converter should be combined with a gas collection system comparable to that devised for the BOF in the steel industry, it would appear possible to obtain gas streams containing sulfur dioxide at concentrations of perhaps 15 to

25 percent, or even higher.

The use of oxygen-enriched air in copper converters makes it possible not only to increase the production of copper from matte, but to smelt additional concentrates autogenously in the converter itself (17D, 41D, 42D). The heat required for smelting comes from oxidation of the sulfur in the ore. Thus, sulfur dioxide that is usually released in low concentrations in the reverberatory furnace is instead released at high concentrations from the converter. Less smelting is required in the reverberatory furnace, which is used primarily to furnish an initial charge of matte at the start of a converter cycle (41D).

At the Hoboken smelter in Belgium, a "Siphon" converter has been developed to replace the conventional Pierce-Smith converter (20D). (Oxygen-enriched air is not used.) The gases are not discharged from the converter mouth but are drawn off through a separate gas offtake having a sealed, rotating joint between the converter and the flue. With only two converters in operation, one blowing at a time, an average sulfur dioxide concentration of 8 percent is attained, with fluctuations about the average of approximately 1.5 percent. With three converters in operation, and two blowing at a time, the average sulfur dioxide concentration is 9 percent, and the fluctuations are about ±1 percent.

Continuous Smelting

A workable process for continuous smelting and converting of copper would have numerous advantages, including easier control of sulfur oxide emissions (24D, 40D). Three proposed processes have drawn attention recently (6D, 31D, 43D), two in western countries (6D, 43D). These would replace the present reverberatory furnace and converter with a single unit supplying a steady flow of gas containing a stable and relatively high sulfur dioxide content. Thus far, the processes have been studied only on a pilot plant scale. The WORCRA process is reported to produce a gas stream containing 9 to 12 percent of sulfur dioxide, depending on the type and grade of the concentrate and on the amount of auxiliary fuel that must be used (43D). Use of oxygen-enriched air presumably could make such a process autogenous and result in still higher sulfur dioxide concentrations in the offgas.

Hydrometallurgy

In the field of hydrometallurgy (or chemical metallurgy), a number of processes are under development that would permit reduction of copper, lead, and zinc sulfides while eliminating part or all of the conventional pyrometallurgical processes that release sulfur oxides (4E, 9E, 12E, 14E). These methods have the added advantage of yielding elemental sulfur as a by-product, which is particularly desirable in areas where markets for sulfuric acid are limited. A number of such processes are described by Habashi (19F).

Copper and elemental sulfur have been recovered directly on a laboratory scale by anodic dissolution of white metal (cuprous sulfide) (8E). The white metal would have to be prepared by smelting of the ore by conventional procedures (see above), and then be cast into anodes. An analogous process is in commercial operation by the International Nickel Company of Canada for reduction of nickel matte (11E, 13E).

Concentrates of sulfide ores can be leached under pressure of air or oxygen and in the presence of sulfuric acid (9E, 10E). The metal sulfates are formed, and the sulfide is oxidized to elemental sulfur. The metal sulfates are separated from the precipitated sulfur and recovered by electrolysis or other appropriate techniques (9E). Such processes are being developed on laboratory or pilot-plant scales for application to chalcocite (15E), chalcopyrite (17E, 18E), zinc blend (7E), and galena (16E). They may prove particularly useful for treatment of complex ores (5E, 9E).

The economics of the pressure leaching processes are reported to be potentially favorable (9E), but to the present no commercial plants have been built for copper, lead, or zinc recovery. The principal engineering problems lie in the design and construction of the autoclaves required for the leaching step (9E, 10E). In large plants, multiple units would probably be required, tending to make capital costs high. The recovery and separation of minor components may also be more difficult than in the pyrometallurgical processes (7B). In the conventional smelting processes, the more volatile components are driven off in the fume (6A, 7B).

Large amounts of copper are currently being recovered by leaching of oxide ores, mine dumps, and other low-grade sources (6E). Most of the dissolved copper is subsequently recovered from solution by cementation (precipitation by addition of iron) (13D, 12E). The precipitated "cement copper" is subsequently smelted by conventional procedures, along with copper ore concentrates (13D). Methods are under development that avoid the cementation step and the subsequent smelting step with its accompanying emission of sulfur oxides (12E). Electrowinning of copper directly from the dilute leaching solutions has usually been uneconomic relative to cementation (13D). However, electrowinning becomes much more economic if the copper can be concentrated into a richer solution. Trials have been made of methods for extracting copper from the lean solutions with a liquid ion-exchange reagent (1E, 4E), and a commercial plant to use such a process in Arizona has been announced (3E). If it is successful, substantial amounts of copper may be recovered by this procedure, particularly in the Arizona area.

Emission Control Systems

Methods for control and useful recovery of sulfur oxide emissions from smelters can for convenience be placed in three categories according to the nature of the sulfur product:

1. Systems producing sulfuric acid,
2. Systems producing concentrated sulfur dioxide, either for use as such or as an intermediate in production of some other material, such as sulfuric acid or elemental sulfur,
3. Systems producing elemental sulfur.

In this review, consideration is restricted to those recovery systems that have been applied to smelters or that appear to have some reasonably favorable current potential for such application. The recovery systems in the latter category are taken to be those that have been applied commercially, though not in smelters, or that have at least been successfully tested on a large scale. The many processes intended for use on flue gases and now in various early stages of development are discussed elsewhere.

Gas Cleaning and Conditioning

The offgases from smelting operations contain not only sulfur dioxide and sulfur trioxide but various amounts of other solid or gaseous contaminants. These other contaminants generally have to be removed from the gas stream prior to sulfur dioxide recovery, either because they have some value themselves or because they may damage the recovery system or contaminate the recovered sulfur product (6A, 11F). The gas itself will usually have to be cooled and, where used in sulfuric acid manufacture, be dried also (13F, 14F).

The waste gases from smelting operations contain varying amounts of mechanically entrained dust as well as fumes formed by vaporization and subsequent condensation of volatile components. The latter include compounds of arsenic, antimony, bismuth, cadmium, mercury, selenium, tellurium, thallium, and other materials in addition to those of copper, lead, and zinc (6A). Most of the dust and fume is recovered in dry-type collectors for its economic value (6A), but the residual quantities escaping the dry dust collectors must be removed to protect any subsequent contact sulfuric acid plant (11F). Any solids will tend to plug the catalyst beds, and some of the compounds tend to deactivate the catalyst as well as contaminate the product sulfuric acid (11F, 13F, 14F). Arsenic, lead, mercury, and selenium are particularly objectionable (11F), Gaseous and liquid contaminants--hydrogen chloride, hydrogen fluoride, and sulfuric acid mist are objectionable, because of their tendencies to attack the catalyst or corrode other parts of the system (11F).

If ore roasting is carried on with a deficiency of oxygen, elemental sulfur may be vaporized and then form a fine fume as the offgases cool. This sulfur fume must also be removed from the gases (11F).

Arsenic trioxide presents a special problem because of its volatility; substantial amounts can be present in the vapor state in the waste gas at temperatures above about 120°C (7F). Donovan and Stuber (11F) present estimated maximum allowable limits for these impurities in gas cleaned for use in sulfuric acid manufacture.

There is no obvious satisfactory way to remove the hydrogen chloride, hydrogen fluoride, and arsenic trioxide without cooling and scrubbing the waste gas. During this cooling and scrubbing, any sulfur trioxide that is not directly collected will form sulfuric acid mist (11F).

The amount of sulfur trioxide formed in the smelting processes is dependent upon residence time, temperature, the amount of excess oxygen, and the presence of metal oxides, such as iron oxide, that may catalyze the oxidation of sulfur dioxide to sulfur trioxide. Restriction of sulfur trioxide formation is favored by limiting the amount of excess oxygen and by rapid cooling of the offgases to temperatures below which the rate of oxidation of sulfur dioxide is low (13F).

Formation of sulfur trioxide is particularly undesirable, because it must be removed as weak sulfuric acid in the gas purification system, where it is usually contaminated with other materials (11F). Unless some way is found to use the impure, weak acid, the loss may commonly be equivalent to 1 to 3 percent of the total sulfur (11F). Recirculation of the scrubbing liquor can theoretically bring the acid concentration up to 50 to 60 percent, but in practice the upper limit is about 25 to 30 percent (11F). If significant amounts of chlorine or fluorine must be removed, the allowable acid strength is further limited to 5 to 10 percent (11F).

The gases emerging from the scrubbing stage are saturated with water vapor, typically at temperatures of 55° to 75°C (11F). Before they can be used in sulfuric acid manufacture, they must be cooled to reduce the moisture content to a tolerable level; this is accomplished by either direct or indirect heat exchange (8F, 11F). The water vapor thereafter remaining in the gas appears in the product sulfuric acid. Consequently, the attainable concentration of the product acid is determined by the temperature of the cooling water and the concentration of sulfur dioxide in the feed gas. It is usually practical to produce 93-percent acid from gas containing at least 3.5 to 4 percent of sulfur dioxide (11F). However, if weaker gas is used, or more concentrated acid is desired, refrigeration is required (11F).

The conventional gas cleaning and conditioning system for a sulfuric acid plant is usually considered to start at the point where the hot dry gas emerges from the collector (usually an electrostatic precipitator or bag filter) used to collect the greater part of the dust and fume in a dry condition (9F). The system consists of (1) one or more scrubbing towers to remove residual dust and contaminant gases and to cool and dehumidify the gas stream, and (2) a wet-type electrostatic precipitator, or two precipitators in series, to remove residual traces of fume and acid mist (11F). A third stage of cleaning is frequently employed; this consists of a packed bed of coke granules or -- in more modern plants -- a fibrous filter, which serves to remove any residual solids or entrained liquid that may escape from the wet precipitator (11F, 14F).

Connor (9F) has given typical capital costs for sulfuric acid plants that show the costs for the gas purification section to be of the same order, or greater, than the costs of an acid-making section handling the same volume of gas. The primary factor determining the cost of the gas purification section is the volume of gas that must be handled. The cost is also shown to be strongly dependent on the amount of heat transfer equipment necessary for the gas cooling step. Consequently, the volume of gas treated should be as small, and the concentration of sulfur dioxide as high, as possible.

Preliminary gas cleaning and conditioning requirements for other sulfur dioxide recovery systems are generally similar to those for contact sulfuric acid plants, but less rigorous. The system used ahead of the Asarco DMA absorption system is essentially the same as that used for a sulfuric acid plant, although the gas does not subsequently have to be dried (17F). At the Cominco lead-zinc smelter at Trail, B.C., the gases to be treated by the Cominco ammonia absorption system are first cleaned by dry collectors, then scrubbed with water and cooled before being admitted to the absorption towers (5A).

Sulfuric Acid Manufacture

The production of sulfuric acid from smelter gases by the contact process is described in numerous literature references (1F, 5F, 11F, 13F, 14F, 15F, 20F, 44F). The chamber process is obsolete and apparently no more than one or two old plants are still in use at smelters in the U.S.

From the standpoint of this review, the most important aspects of the contact process are those related to the concentration of sulfur dioxide in the entering gas. A contact sulfuric acid plant can be made autothermal if the gas contains at least 3.5 percent of sulfur dioxide; that is, the heat generated by the oxidation of the sulfur dioxide to sulfur trioxide can be exchanged to preheat the incoming feed gas to a temperature sufficiently high for the oxidation reaction to start at an adequate rate (11F, 13F). When the sulfur dioxide concentration is lower than this critical level, it is necessary to add supplementary heat from some other source. Acid plants fed with copper converter gases frequently operate near the thermal balance point, or sometimes below it (14D, 44F). The problem is increased by the fluctuations in both gas volume and sulfur dioxide concentration that result from the cycle of copper converter operation (13F, 44F). In some cases it has been necessary to operate a fuel-fired preheater on a continuous or nearly continuous basis (44F). Operation near the thermal balance point requires a large amount of heat transfer surface in the heat exchanger system.

The problem of water balance, which determines the concentration of product acid attainable with dilute gas feed, is described above.

The size, and hence the cost, of a contact plant is determined primarily by the volume of gas that must be handled; the acid production capacity of a given plant is determined by the concentration of sulfur dioxide in the feed gas (9F). The ratio of cost to capacity therefore drops as the sulfur dioxide concentration increases, within limits. However, gases containing more than about 8 to 10 percent of sulfur dioxide are usually deficient in oxygen, and it is necessary to add air to provide the excess of oxygen necessary for favorable conversion of the sulfur dioxide (9F, 13F). Consequently, the size of the acid-making section of a plant is not much changed as the sulfur dioxide content of the original feed gas rises above 8 to 10 percent (9F). However, the size of the gas purification section is reduced, as noted above (9F).

At the Trail, B.C., smelter of Cominco, Ltd., the capacity of the sulfuric acid plants has been increased by enriching the feed gas with concentrated sulfur dioxide from the Cominco absorption system (5A). One of the sulfuric acid plants is operated on sulfur dioxide and oxygen. The exit gas is recycled except for a small purge stream that carries off nitrogen accumulating from residuals in the oxygen and sulfur dioxide feed gases. The purge gas is vented through the Cominco absorber.

The design efficiency of conversion of sulfur dioxide to sulfur trioxide in conventional contact sulfuric acid plants may be as high as 98.5 percent (12F), but is frequently lower (6F, 12F). In plants operated at throughputs greater than those designed for -- a common practice -- the actual conversion efficiency obtained may be substantially below the design figure (6F, 12F). Consequently, the emissions of sulfur dioxide in the tail gases of sulfuric acid plants may themselves be a substantial source of air pollution (5A, 27F, 34F). Two general approaches to control have been used. One, discussed below, is to use a secondary scrubbing system to remove the residual sulfur dioxide from the tail gas. Another, already in use abroad, is the use of the "double-contact" or "interpass-absorption" system in the acid plant itself, as described in a number of recent publications (12F, 25F, 32F). After a first stage of conversion, the sulfur trioxide formed is absorbed; then the gas is reheated and passed through a second stage of conversion before the final absorption step. By this procedure it is possible to raise conversion efficiency to at least 99.5 percent (12F, 32F).

With the interpass-absorption system it is necessary to have a higher sulfur dioxide concentration (at least 6 percent) to attain autothermal operation than is the case for the conventional type acid plant (12F). At concentrations under 7 percent, large heat exchangers are required (12F).

Numerous processes other than the contact process have been proposed for production of sulfuric acid from gases -- particularly power plant flue gases -- that contain low concentrations of sulfur dioxide (13F, 43F). The problem common to these processes is that they produce dilute acid that must subsequently be concentrated if it is to be shipped any appreciable distance for sale. The concentration step requires substantial additional capital and operating costs (13F, 14F).

Two processes in this category that are relatively simple in principle have drawn attention recently. The Lurgi Sulfacid process has come into use in several European chemical plants for control of gases containing less than 0.2 percent of sulfur dioxide (38F). The cleaned, saturated, and cooled gas (at about 160°F) from a scrubber or saturator is passed through a wetted bed of active carbon, where the sulfur dioxide is adsorbed and catalytically oxidized to sulfuric acid. The carbon bed is flushed with enough water to remove the acid as it is formed. The acid produced has a concentration of only about 8 to 15 percent sulfuric acid, and must be concentrated unless there is some immediate use for it as produced. In some cases the concentration can be effected by using the weak acid in the preliminary scrubber-saturator (38F). However, in smelter applications this step would produce a highly contaminated acid.

The Monsanto Cat-Ox process (41F), an adaptation of the contact process, was designed for use on gases (primarily flue gases) containing low concentrations of sulfur dioxide. The gas is cleaned in a high-temperature electrostatic precipitator, then admitted to the catalytic reactor at about 900°F. The gases from the converter are cooled in a heat exchanger, then pass into an absorption tower where the sulfur trioxide is absorbed in recirculated sulfuric acid and the gas temperature is further reduced. The exit gases from the absorption tower pass through a Brink mist eliminator for collection of the remaining sulfuric acid mist.

The system has been tested on a prototype scale (24,000 std cu ft/min of gas) at a coal-fired power plant (41F). The efficiency of collection of sulfur dioxide was 90 percent, apparently the design figure, and the concentration of the acid produced was 80 percent. In this system, the initial temperature of the stack gas is high enough to permit the catalytic oxidation of the sulfur dioxide to take place, and the source of the water for formation of the acid is the moisture in the combustion gas itself.

From the standpoint of possible application to smelters, the critical aspect of the Cat-Ox process is probably the gas purification step. The smelter gases will in virtually all cases contain substantial quantities of zinc and lead oxides, which are difficult materials to collect in an electrostatic precipitator and are also potent catalyst poisons. In addition, volatile and gaseous contaminants (arsenic trioxide, hydrogen fluoride, and hydrogen chloride, in particular) may either affect the catalyst or damage the other equipment, and will in any case contaminate the product acid. There is no obvious way to eliminate these materials ahead of the Cat-Ox converter so long as the gas stream is kept hot, as it must be. Finally, the product acid is still relatively dilute.

Concentration of Sulfur Dioxide

For recovery of sulfur dioxide as such, a cyclic absorption system is economically advantageous and a number of such processes have been developed and used (21F). However, the economics of regeneration of the absorbent can easily determine the overall economics of the recovery process. The simplest procedure employs stripping of the absorbent with steam, but chemical regeneration methods are also used (21F). The choice of absorbent is dependent upon the initial concentration of the sulfur dioxide in the gas stream. Those absorbents that afford a favorable equilibrium for removal of sulfur dioxide at low concentrations will also tend to require excessive amounts of steam for regeneration. On the other hand, absorbents having equilibria and capacities favorable for recovery of sulfur dioxide present at high concentrations in gas streams will be at a disadvantage in the recovery from dilute streams (21F, 22F).

There are two principal regenerative absorption processes in commercial use for recovery of sulfur dioxide from smelter gases. One uses a solution of ammonium sulfite-bisulfite as the absorbent (5A, 26F, 27F).

As developed by Cominco, this process employs chemical regeneration with sulfuric acid to release sulfur dioxide with formation of an equivalent amount of ammonium sulfate (26F, 27F). Attempts to operate such a system with thermal regeneration, and without major net chemical consumption, apparently proved technically unfavorable and relatively uneconomic (5A, 10F, 21F).

The Cominco absorption process has been used to treat zinc roaster gases containing as much as 6 percent of sulfur dioxide (5A, 30F), but its most important application has been in recovering sulfur dioxide at concentrations of 1 percent or less from lead sintering machine gases (5A, 30F) or sulfuric acid plant tail gases (5A). The economics of the process are strongly dependent upon the existence of adequate markets for the ammonium sulfate produced (25F).

Processes for recovering sulfur dioxide at concentrations of about 3 percent or more from smelter gases have been used either to supply favorable local markets for liquid sulfur dioxide, or as a preliminary to reduction to elemental sulfur. The principal process in use is the Asarco DMA absorption process (17F), which employs anhydrous dimethylaniline as the absorbent and is relatively complex. In the U.S. it is in limited use for production of liquid sulfur dioxide from lead and copper smelter gases (17F), but a unit is reported (39F) to be employed at a Spanish smelter to concentrate sulfur dioxide for subsequent reduction to elemental sulfur.

The DMA process has been used on waste gases containing about 4 to 5 percent of sulfur dioxide (9B, 17F). The equilibrium between dimethylaniline and sulfur dioxide is unfavorable for economic recovery of sulfur dioxide from gas streams containing less than about 1 to 2 percent (17F). However, the capacity of the solvent is good when initial sulfur dioxide concentrations are high. The equilibrium curve (17F) indicates that if the sulfur dioxide concentration were 8 to 9 percent, the recovery process should be markedly more economical than it is in the range of 4 to 5 percent where it is commonly being used.

The Lurgi Sulphidine process (4A, 10F, 33F) is somewhat similar to the Asarco DMA process. The absorbent is a suspension of xylidine in an equal weight of water. The equilibrium with sulfur dioxide is more favorable than that of dimethylaniline at sulfur dioxide concentrations below 3.5 percent, but much less favorable for concentrations above that level (17F). The process was reportedly adapted to use on gases containing from 1 to 16 percent of sulfur dioxide (10F). The Sulphidine process was used on a limited scale in Germany prior to World War II to recover sulfur dioxide from copper converter gases (4A, 10F, 33F). It may no longer be in use.

Imperial Chemical Industries developed a cyclic absorption process using a solution of basic aluminum sulfate as the absorbent (4F, 42F). The absorbent had less capacity for sulfur dioxide than either dimethylaniline or the xylidine-water suspension and was suitable for use only on the richer gases (4F, 17F, 42F). The basic aluminum sulfate process was used at a copper smelter in Finland for several years prior to World War II, recovering sulfur dioxide in 5 percent initial concentration from converter gases (4A, 33F).

A problem common to the various cyclic absorption plants is the oxidation of part of the sulfur dioxide or sulfites to sulfates (4F, 10F, 17F, 21F, 40F). The sulfates cannot be readily regenerated and must be purged from the absorbents by various techniques (4F, 17F, 42F). The oxidation results in large part from the presence of oxygen in the gas, and is especially troublesome with dilute gases containing large amounts of excess air (4F, 17F). This problem should be much reduced if the smelter gas has little residual oxygen and air infiltration is avoided. The oxidation of the sulfite is not a serious problem with the Cominco absorption system because ammonium sulfate is one of the normal products.

Reduction of Sulfur Dioxide

Reduction of sulfur dioxide to elemental sulfur has been practiced commercially at a number of smelters (4A, 5A). Apparently the processes used have never been very favorable economically, and have been used only where the necessity for air pollution control has been paramount and no adequate market has existed for sulfuric acid.

The reducing agents used have been coke, producer gas, and natural gas. In the Boliden process (4A, 4F, 42F), operated in Sweden for several years prior to 1943, roaster gases containing 9 percent of sulfur dioxide and 5.5 percent of oxygen were introduced directly into the system and reduced with producer gas. The producer gas was formed by passing a portion of the roaster gas through coke in a gas producer (42F). Because the feed gas was dilute in sulfur dioxide and relatively high in residual oxygen, the consumption of coke was high (4A).

The most notable application of sulfur dioxide reduction was at the Cominco smelter at Trail, B.C. (4A, 5A, 28F, 29F). Essentially pure sulfur dioxide concentrated by the Cominco absorption system was introduced into a coke-fired reduction furnace along with some oxygen (5A). The reduction reaction was not sufficiently exothermic to be self-supporting, and the oxygen was added to provide heat by its reaction with part of the coke (5A, 29F). The consumption of coke was much lower than that of the Boliden process. The reduction process was operated at Trail from 1935 to 1943, when the market for sulfuric acid became large enough to absorb the sulfur dioxide output of the smelter (4A, 5A). It is still being used in Spain to reduce sulfur dioxide from a smelter (39F).

In the reduction of sulfur dioxide, carbonyl sulfide and hydrogen sulfide were formed in the furnace by the reaction of the sulfur dioxide with coke, or carbon monoxide, and water vapor (5A, 29F). Small amounts of carbon disulfide were sometimes formed, also (5A). The gases from the furnace were cooled and passed through catalytic reactors at appropriate temperatures to permit the carbonyl sulfide and hydrogen sulfide to react with sulfur dioxide to form sulfur (5A). However, since the reactions did not go to completion, the tail gas from the Cominco reduction plant eventually had to be incinerated to eliminate the unconverted carbonyl sulfide and hydrogen sulfide (5A). Electrostatic precipitators were used to remove sulfur mist from the tail gases of both the Boliden and Cominco reduction plants (5A, 42F).

Extensive pilot plant studies have been made of processes for reducing sulfur dioxide with natural gas (16F, 35F, 46F), and such a system will soon go into commercial operation at Sudbury, Ontario (2F, 3F).

The Asarco Brimstone process (16F) was operated on a semicommercial scale on copper roaster gas (7.25 percent sulfur dioxide) and copper converter gas (5.5 percent sulfur dioxide). Sufficient natural gas was added to consume the residual oxygen in the feed gas and to convert the sulfur dioxide present to elemental sulfur. Combustion at high temperature took place in a furnace, after which the gases were cooled and successively passed in stages through three catalytic reactors to complete conversion of carbonyl sulfide and hydrogen sulfide. The gases were cooled and sulfur was condensed following each catalytic reactor.

In the Asarco process a relatively large amount of natural gas had to be burned simply to bring the feed gas and the remainder of the natural gas up to the temperatures required in the reaction furnace. The oxygen content of the feed gas therefore had to be relatively high (16F).

Texas Gulf Sulphur Company developed a process generally similar to the Asarco Brimstone process except that the first-stage reaction furnace is replaced by one or two catalytic reactors operating at relatively low temperature (46F). The TGS process is designed to be used on concentrated and oxygen-deficient streams of sulfur dioxide as well as on the dilute streams used in the Asarco process. Preheating of the gases entering the first-stage catalytic reactor is accomplished by heat exchange with the hot gases leaving the reactor, although additional natural gas and oxygen or air can be burned directly in the feed gas stream if desired (46F). The second- and third-stage catalytic reactors for conversion of carbonyl sulfide, carbon disulfide, and hydrogen sulfide are similar in principle to those in the Asarco process.

The TGS process was studied on a pilot plant scale at Copper Cliff, Ontario, using the offgas from a fluid-bed pyrrhotite roaster (35F). The gas entering the pilot plant contained 10.3 percent of sulfur dioxide and only 3.3 percent of oxygen (46F). Apparently the process was technically successful but not economically attractive at the time it was developed (2F).

The commercial reduction plant at Sudbury, Ontario, is to go into operation in late 1969 (3F). The process, to be installed by Allied Chemical Canada, Ltd. (2F), is not described but is probably basically similar to the TGS process. It will operate on pyrrhotite roaster gases, without preconcentration of the sulfur dioxide, which will probably have a concentration of about 10 to 12 percent, as at the Copper Cliff installation. The adoption of the reduction process was probably determined by the combination of the need to control air pollution and of the potential problems and cost of shipping the alternative by-product, sulfuric acid, from Sudbury to the market area in the lower Great Lakes.(3F).

The feed gases to the various reduction processes all received a greater or lesser degree of precleaning (16F, 42F, 46F). The gas fed to the Asarco plant was cleaned to the same degree required for feed to a sulfuric acid plant, but was not dried (16F). Like the Boliden and Cominco processes, the Asarco process employed electrostatic precipitation to remove sulfur mist from the cooled gases (16F). Three precipitators were used in the Asarco semicommercial plant, one following each stage of sulfur condensation (16F).

Except for the first-stage furnace or reactor, the sulfur dioxide reduction processes using natural gas are very similar to the modified Claus process (18F, 36F, 45F) for production of elemental sulfur from hydrogen sulfide. This similarity holds particularly where the Claus process is operated on relatively lean gas streams containing carbon dioxide and residual hydrocarbons. Probably much of the technology and experience from the Claus process is applicable to sulfur dioxide reduction plants. In the Claus plants it has apparently never been necessary to use electrostatic precipitators to remove sulfur mist from the tail gases, even in cases where the feed stream of hydrogen sulfide was relatively dilute (18F). However, the reactions of the sulfur dioxide with the carbonyl sulfide, carbon disulfide, and hydrogen sulfide do not go to completion, and the tail gases have to be incinerated to convert the latter three compounds to sulfur dioxide, which is less toxic and obnoxious (45F). In order to reduce atmospheric pollution from Claus plants, three catalytic reactors, rather than two, are sometimes used to increase the conversion to elemental sulfur (18F, 45F). The situation is similar to that at sulfuric acid plants, where the extent of conversion is also limited by the thermodynamics and kinetics of the reactions.

The economics of sulfur dioxide reduction plants are probably strongly dependent upon the credit that can be taken for waste heat recovery, particularly in the cases where dilute gases are being treated. Both the Cominco and the Asarco reduction plants were equipped with waste heat boilers (5A, 16F). It was considered that the Asarco process could be regarded in large measure as a power-generating process when operated on low-grade gas (16F). The heat that could be recovered as steam was estimated to be over 40 percent of that which could be generated by burning an equivalent amount of natural gas directly under a boiler (16F).

It is obvious that the capital and operating costs of a reduction plant fed with concentrated sulfur dioxide will be lower than for a plant fed with gas having a low concentration of sulfur dioxide. However, the savings must be balanced against the added cost of concentrating the sulfur dioxide from the original dilute gas stream. At the low end of the sulfur dioxide concentration range, a combination of preconcentration and reduction should have the lower overall cost. As the concentration of the sulfur dioxide in the smelter gas increases, a level will be reached at which direct reduction without preconcentration will have the lower overall cost.

Sulfur dioxide can also be reduced by reaction at high temperatures with sulfide ores such as pyrite or pyrrhotite; the literature has been reviewed by Habashi (19F). Processes for employing such reactions have been studied on a laboratory or pilot plant scale (31F, 37F), primarily for recovery of elemental sulfur from pyrite, but have apparently never been commercialized. The reactions do not go to completion (23F), and hence the offgases containing unreacted sulfur dioxide must be recycled after the sulfur has been removed by condensation (19F, 31F, 37F). The reduction of the sulfur dioxide can, of course, be made part of a process for recovery of the metals in the ores.

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